2008-09

Improving situational awareness on submarines using augmented reality

Hatt, Ronald V.

Monterey, California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

IMPROVING SITUATIONAL AWARENESS ON SUBMARINES USING AUGMENTED REALITY

by

Ronald V. Hatt

September 2008

Thesis Advisor: Joseph Sullivan
Thesis Co-Advisor: Mathias Kölsch

This thesis was done in cooperation with the MOVES Institute
Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2008	**3. REPORT TYPE AND DATES COVERED** Master's Thesis
4. TITLE AND SUBTITLE Improving Situational Awareness on Submarines Using Augmented Reality		**5. FUNDING NUMBERS**
6. AUTHOR(S) Ronald V. Hatt		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A		**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

Modern submarines are complex machines operating in a harsh environment. Although technology has been rapidly introduced in the submarine fleet, submariners must process more information due to increases in sensor capability and information available for decision-making. Unfortunately, improvements in the human-systems interfaces have not kept up with the new technology. Incidents involving human error are still occurring at an unacceptable rate in the modern fleet. This thesis addresses the deficiency in display information that occurs for the key decision maker in control, the Officer of the Deck. The results from a cognitive task analysis (CTA) provide insights on the information flow and display uses for the critical periscope depth procedure. This thesis also identifies the Level of SA associated with each step of the CTA. An analysis of the data from the CTA provides the deficiencies of the current system and suggests that the breakdown of SA occurs at Level 2. Through subject observations and personal experience, the author details the required information necessary for the OOD to make prompt decisions in control. This thesis attempts to provide an answer to the information display problem by introducing the emerging technology of augmented reality as a candidate solution.

14. SUBJECT TERMS Augmented Reality, Submarine, Human Systems Integration, Human Factors, Cognitive Task Analysis			**15. NUMBER OF PAGES** 121
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

IMPROVING SITUATIONAL AWARENESS ON SUBMARINES USING AUGMENTED REALITY

Ronald V. Hatt
Lieutenant, United States Navy
Bachelor of Science, The Citadel, 2001

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MODELING VIRTUAL ENVIRONMENTS AND SIMULATION (MOVES)

from the

NAVAL POSTGRADUATE SCHOOL
September 2008

Author: Ronald V. Hatt

Approved by: Joseph Sullivan
Thesis Advisor

Mathias Kölsch
Co-Advisor

Mathias Kölsch
Chair, MOVES Academic Committee

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Modern submarines are complex machines operating in a harsh environment. Although technology has been rapidly introduced in the submarine fleet, submariners must process more information due to increases in sensor capability and information available for decision-making. Unfortunately, improvements in the human-systems interfaces have not kept up with the new technology. Incidents involving human error are still occurring at an unacceptable rate in the modern fleet. This thesis addresses the deficiency in display information that occurs for the key decision maker in control, the Officer of the Deck. The results from a cognitive task analysis (CTA) provide insights on the information flow and display uses for the critical periscope depth procedure. This thesis also identifies the Level of SA associated with each step of the CTA. An analysis of the data from the CTA provides the deficiencies of the current system and suggests that the breakdown of SA occurs at Level 2. Through subject observations and personal experience, the author details the required information necessary for the OOD to make prompt decisions in control. This thesis attempts to provide an answer to the information display problem by introducing the emerging technology of augmented reality as a candidate solution.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to acknowledge the tremendous efforts of my thesis advisors CDR Joe Sullivan and Dr. Mathias Kölsch. I am sure they are thankful that I am finished with this process. They suffered many impromptu sit-ins to discuss the direction of my work. Thank you again.

Dr. Mike McCauley and Dr. Tony Ciavarelli provided direction and support that contributed heavily to this work. Although these gentlemen were not my advisors on paper, they patiently listened and humbly presented solutions and help that ultimately led to the completion of this work. Thank you very much for taking the time out of your busy schedule for me.

My fellow students have provided a source of laughter and cynicism that have often brought me to tears. Thank you all for both. Special gratitude goes to Majors Brian Kibel and Eric Whittington for the countless hours spent discussing and researching “other” modeling and simulation activities.

I would also like to express my deep love and adoration of my beautiful wife who patiently waited for me at home with our children, while I worked long hours to complete this research. Without her, none of my accomplishments are possible. Becky, you are certainly a remarkable woman that I will love forever.

And lastly, I thank God for giving me the opportunities that I so often don’t deserve. Thank You for Your Grace. Thank You for my family, my career and my education. I love You.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. MOTIVATION

Since the year 2000, the submarine force has been involved in navigational incidents that have resulted in millions of dollars spent in avoidable repairs and the unfortunate loss of lives. The impact of the following two navigational incidents was severe to the submarine force.

1. The USS San Francisco

In January 2005, the Los Angeles class submarine USS San Francisco (SSN 711) collided with an underwater seamount while traveling at maximum speed and at a depth of 525 feet (7th Fleet 125). A sailor lost his life and 97 other crewmen suffered injuries. The destruction to the bow of the submarine was so severe the ship was nearly lost. Fortunately, for the crew, the internal pressure barrier hull was undamaged. The ship surfaced and returned to port in Guam for a detailed damage assessment. The Navy estimated that the ship would remain out of service for more than 400 days and that final repair costs will be greater than $88 million (7th Fleet 125).

Figure 1. The USS San Francisco After Grounding on January 8, 2005 [From Navy NewsStand]

The command investigation findings stated that the navigation team and command leadership failed to use proper procedures. Specifically, the navigation team prepared the navigational chart for use without reviewing all charts available for the locale (7th Fleet 126). This is a procedural requirement to ensure that all sources are reviewed for potential navigation hazards prior to planning the ship's intended route. Additionally, the inquiry found a stain obscuring the visibility of the seamounts location on the chart used for navigation (7th Fleet 126). A proper review of the navigational track would have identified this deficiency in preparation techniques. The command leadership is required to review charts to ensure these procedures are strictly followed.

The leading cause of the incident was that the crew lacked the necessary situational awareness for safe ship handling. The control room watch team was unable to fuse the static and dynamic information required to build SA. The command-level chart-review process was inadequate (7th Fleet 126). Therefore, the information provided to the watch team as valid environmental data was actually false and misleading. Excess hull noise generated at high speeds obscured information that could have prompted the control room watch team to take action and prevent the grounding (7th Fleet 126). In short, the watch team was driving blind. Improving control room displays would have allowed for better decision-making on the watch team members.

2. The USS Greeneville

In February 2001, the Los Angeles class submarine USS Greeneville (SSN 772) collided with the Japanese vessel Ehime-Maru (Pac Fleet). The USS Greeneville was conducting an emergency main ballast tank (EMBT) blow demonstration for the 16 civilians that were onboard for a VIP visit (Pac Fleet). Nine Japanese crewmembers lost their lives and the Ehime-Maru was sunk (Pac Fleet). The incident strained international relations between the United States and Japan because CDR Scott Waddle's, the Commanding Officer (CO) of the

USS Greeneville, delayed apology was inconsistent with Japanese culture. The ship lost more than two months of operational time Damage to the rudder and hull totaled $2 million (Pac Fleet).

There were several reasons for this tragedy. The court of inquiry findings stated that Waddle inappropriately assumed control of the ship during the evolution (Pac Fleet), even though it is normal for the Officer of the Deck (OOD) to maintain control of the ship. The court also found that Waddle placed undo urgency on completing the evolution (Pac Fleet). This urgency suppressed the forceful backup normally provided by the control room watch team. A watch team member knew that a vessel was close and he failed to pass the information to Waddle (Pac Fleet). Waddle failed to have a full understanding of the contact picture while at periscope depth. Waddle used an unapproved periscope procedure to check for visual contact prior to ordering the ship to go deep (Pac Fleet).

A control room watch team member did not have a full understanding of the contact picture as well. The Combat Control System (CCS) operator was unable to correctly recall the contact numbers. In addition, the same operator changed the contact's range from 3,000 to 9,000 yards based on false information. The contact was the Ehime-Maru. The control room watchstanders on the USS Greenville clearly lacked the required information to assist in the safe navigation of their vessel.

The underlying cause of the described above was poor control room watch-stander situational awareness. Submarine operating procedures are used in order to ensure situational awareness is maintained. Waddle failed to update his mental model of his ship's environment by failing to follow procedure. Urgency, whether required or not, stresses a person's ability to maintain proper situational awareness. The watch team member could not maintain the correct sonar contact numbers during a routine evolution. Maintaining sonar contact numbers is a common practice in modern submarines. In environments managed by watch teams, situational awareness is shared. Waddle did not have

shared situational awareness. Waddle's mental model was inaccurate because a watch team member failed to pass information to Waddle needed for safe navigation of his vessel.

B. PROBLEM STATEMENT

These two serious and fatal submarine incidents provide some evidence that the control room watch team does not have the necessary tools to build and maintain proper situational awareness (SA) to consistently navigate submarines safely. Some might argue that the incidents described above are rare considering the thousands of hours of safe submarine navigation. As a submarine force, we should be looking for better ways to ensure the safety of our fleet, our crews and all those who travel by sea. The submarine force has had a significant number of improvements in sonar capabilities and combat systems integration. However, the deficiencies that still exist in the submarine control room displays inhibit watch team SA.

A submarine OOD evaluates a large amount of environmental information to navigate his craft safely and to complete the ship's mission effectively. It is necessary for the OOD to observe the environment through shipboard sensors, comprehend the data observed and make predictive models in order to maintain SA. The OOD then uses SA to choose his next course of action. After taking the action decided upon, the OOD starts the process again.

Although most military task domains use SA for the same goals as described above, the construction of the mental model is very different. A submarine OOD, when operating his craft submerged, requires the same information a surfaced craft requires to navigate the ship safely. Since the majority of submarine navigation operations are underwater, the OOD's ability to view his outside world is restricted to that which he internally constructs using information provided by various sensors. The OOD builds a mental model of his surrounding from sensor information such as sonar displays, combat systems displays and periscopes. What makes the submerged OOD mental model

problem unique is that he is unable to visualize the vessels affecting his decisions. Therefore, the amount of information to build and maintain the mental model can be overwhelming. It can be so overwhelming that it is common to station in control an additional two officers to assist the OOD with information processing for mental model construction and decision-making.

The OOD constructs a user-centric mental model. This model is the natural model chosen for this process. The OOD mentally places the vessels detected by the sensors in the corresponding positions around the ship. The OOD assigns the correct bearing rate with an approximate range and the model is sufficient. Bearing rate and an approximate speed can provide a course. Decisions on how to steer the submarine to avoid collision become easier using this model. The OOD can make predictions on where contacts will be if this model is maintained correctly. With predictions estimated from the mental model, the OOD can direct a steer early in order to prevent collisions with other crafts. If the OOD employs the user-centric model efficiently, he is also able to share this mental model with the watch team as well. To discuss the location of a contact, the OOD recalls the approximate bearing to the contact, points in its direction, and signals the bearing drift by using hand gestures and verbally indicates the current bearing rate to the watch team.

There are some difficulties the OOD manages using the user-centric model. A difficulty in employing a user-centric model for contact management is that bearing rates for contacts are not constant over time and the OOD uses bearing rates to build the initial model. For contacts that are distant, bearing rates are relatively constant. However, for the same contact, as the contact moves closer, the bearing rate will increase until the contact reaches the closest point of approach. Then after passing the contact, the bearing rate will decrease again. This is relative motion. Another difficulty involving relative motion with a user-centric model is that the OOD is making decisions without vision. Humans are good at perceiving relative motion with vision. Drivers behind the wheel of a car use a user-centric model well to make predictive choices to avoid collisions

with other drivers. A driver makes subtle acceleration changes, with little cognitive focus, to avoid collision with a vehicle that slows in front of the driver. Imagine driving blindfolded with another person describing the other cars that are on the road as bearings and bearing rates. To the novice, the task is very challenging.

The user-centric mental model is regularly interfered by a number of factors including, but not limited to, new contact information and changes of the ship's state. These disruptions of the OOD's mental model often results in the reconstruction of the model, taking time from the decision-making process. Often the OOD is required to change the ship's course. The relative positions of vessels tracked change in a user-centric model after course changes. Common updates such as this are time consuming. Even experienced OODs often require a complete reconstruction of the environmental model in an environment with many contacts.

The internal model-making process also makes it difficult to provide a common or shared model to a watch team. Due to the extreme environments in which submarines operate, the watch team concept becomes vital to help the OOD make the right decision with the right information (this is referred to as "backup"). It becomes imperative that the watch team has a shared picture in order to provide the proper backup, especially in the case that the picture is faulty. The most common practice of communicating the OOD's mental model is by verbally describing the model to the watch team. This process interrupts the watch team members and can take time away from their independent decision-making processes.

A display that described the shared picture of the ship's operational environment is available on submarines. However, the displays used often vary from ship to ship, and not all shipboard displays are viewable from all watch team members' stations. This often results in verbal communications that can obstruct

the decision-making process as well. To avoid interrupting the OOD and his decision-making process, members often leave their stations to view the "shared" environmental picture.

The current submarine control room display system forces the environmental model making process on the primary decision maker. Submarine OODs have been using user-centric mental models effectively to navigate their crafts for many years. However, the process is cognitively expensive to maintain. Common adjustments in ownship's parameters, such as changing course, often require reconstituting the mental model. The mental model process takes away valuable time from the OOD during critical tasks. Sharing the model with the watch team interrupts the OOD and the watch team.

C. RESEARCH QUESTIONS

The analysis described in the problem statement as well as my experience operating a nuclear submarine as OOD has driven the questions pertaining to my research. Increasing SA for the control room watch team is also a submarine force focus. The questions that specifically motivated this thesis work include:

1. What information is the OOD currently using to make decisions?
2. What displays are the OOD looking at to get the information?
3. What communications are required to gain the information?
4. What information is required by the OOD to make prompt decisions?
5. Is this information immediately available during critical evolutions?
6. If not, what is the best way to provide this information?

D. THESIS ORGANIZATION

Chapter II provides some background information on the related topics that are covered in this thesis. Chapter III is the literature review conducted to support the research. Chapter IV discusses the methods used to conduct the

cognitive task analysis (CTA) for the submarine control room watch team. Chapter V reviews the results of the CTA. Chapter VI discusses the current system deficiencies and the areas identified for adding improvements. Chapter VII identifies a possible solution using Augmented Reality for the improvements identified in Chapter VI. Chapter VIII discusses conclusions and recommendations for future work.

II. BACKGROUND

A. SITUATIONAL AWARENESS

Several individuals have developed a definition of SA for specific fields. However, the original definition by Mica Endsley is still widely accepted. Endsley defines SA as *"the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* (*Theory* 36). A more simple definition is, "*knowing what is going on so you can figure out what to do*" (Adam 319). In submarine control rooms, SA is therefore the model the watch team develops of the ship's environment. Additionally, Endsley's definition identifies three elements that delineate three different levels of SA:

- Level 1: Perception of elements in the environment,
- Level 2: Comprehension of the current situation,
- Level 3: Project of future status (Theory, 35).

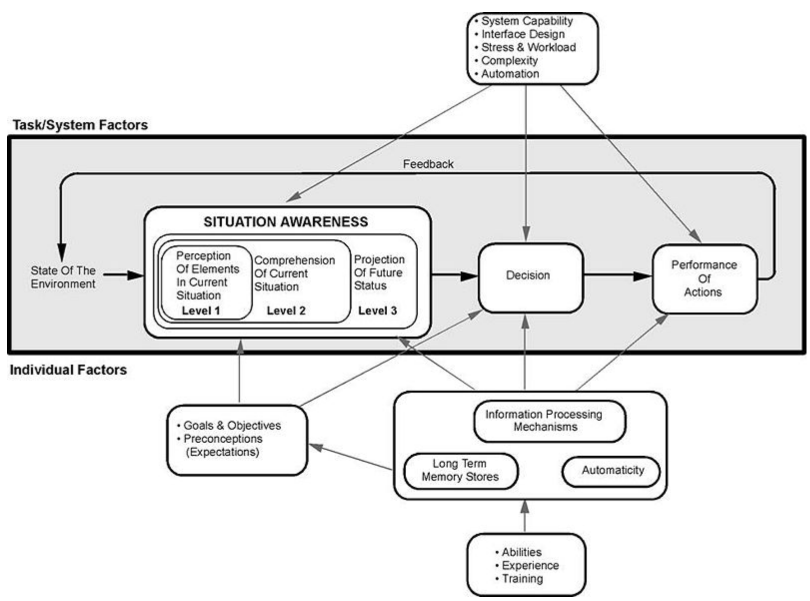

Figure 2. A Diagram of Situational Awareness and its Relation to the Individual and Environment [From Endsley, *Theory* 35]

With respect to control room watch teams, Level 1 SA is considered to be perception of all contact's information detected by the sonar system, i.e., each contact's bearing, bearing rate, speed and classification. Level 2 SA is then information extracted from these perceptions such as contact course, range and speed limitations based on its classifications. Level 3 SA is predicting the future of the contact picture based on Level 1 and Level 2 SA. An OOD can use the information gained from perception to build an understanding of what a contact is doing to predict the future proximity of the contact to the OOD's ownship. Therefore, the OOD can steer the ship early to avoid a collision with the incoming contact.

In the USS Greeneville collision described in the previous chapter, a CCS operator that failed to maintain contact numbers. This is a Level 1 SA error. The same operator, receiving a false report, altered the range of the Ehime-Maru from the estimated, and nearly accurate, 3,000 yards to 9,000 yards. The operator committed a Level 2 error by allowing someone else judgment to position the contact further away, when he had indication the contact was close. Then because of the breakdown of Level 2 SA, the operator fails to make the necessary prediction that the sonar contact, Ehime-Maru, is within range to collide with the ship. This Level 3 error became more likely to occur because of the hierarchical properties of the levels of SA. Once a lapse in Level 1 or Level 2 SA occur, the Level 3 error is likely to occur as well.

B. SUBMARINES

The U.S. Navy has a diverse arsenal of submarines. The U.S. submariner can operate up to five classes of ships, and, in some classes of ships, there are different variations of the class. The Los Angeles (LA) class submarine, the oldest "fast attack" submarine still in service, has two variations of design called "flights." The second flight LA submarine has the Vertical Launch System that gives the submarine the capability to launch more weapons. Another fast attack class is the Sea Wolf class, of which there are only three in operation (Jane's

883). The Sea Wolf class is a Cold War relic that is very capable of delivering superior force under the sea. Unfortunately, U.S. Congress deemed the Sea Wolf class too expensive to build at more than $2 billion each (Jane's 884). The Virginia class submarine is a low cost replacement for the Sea Wolf. It has a modular design in support of multi-mission requirements such as littoral and deep-water operations (Jane's 882). The Virginias will eventually replace the aging LA class submarines at a production rate of about two per year. The Ohio class submarine is the only ballistic missile submarine in the U.S. submarine arsenal. The U.S. Navy has converted four of the Ohio class submarines to guided missile submarines (Jane's 881).

Controlroom display systems are not congruent in the U.S. submarine force. On each submarine platform, there exist different fire control and sonar systems. Each system displays information differently. Throughout the five classes of submarines, there exist five different sonar suites and five different combat systems. The ships of the LA class alone have three different types of sonar suites and combat systems (Jane's 884). The U.S. Navy has updated the processing power of the legacy sonar suites. However, it has not updated the displays for some ships since the construction of the vessel. The same dilemma affects the submarine fire control systems.

1. Submarine Displays

a. Auxiliary Sonar Visual Display Unit

The Auxiliary Sonar Visual Display Unit (ASVDU) is located in control and is the primary source of information for the OOD. External noise detected by sonar is displayed by true or relative bearing over time. The monochromic display has a "waterfall" aspect. As time advances, the brightened pixel that represents the detected noise falls along with the line of other pixels that occupied the topmost portion of the display to make room for the next pixel line of noise. The pixel line represents 360 degrees noise detection around the

ship for a unit of time. The unit of time the line represents can be altered. Each trace that forms over time varies in width depending on the level of noise that is emitted from the contact compared the background noise surrounding the contact. Therefore, a relatively loud contact compared to the surrounding ocean environment will have a wider trace. This is commonly referred to as “a contact is burning in.” Which means the contact is loud or close.

The ASVDU is the primary source of information to the OOD for one primary reason. The data displayed on the ASVDU is unprocessed. The ASVDU displays bearing data for all contacts. The OOD uses the waterfall display to calculate instantaneous bearing rate for a contact as well. All other bearing and bearing rate source displays have processed information.

The ASVDU satisfies Level 1 SA. It displays raw sonar information such as contact bearing and bearing rate.

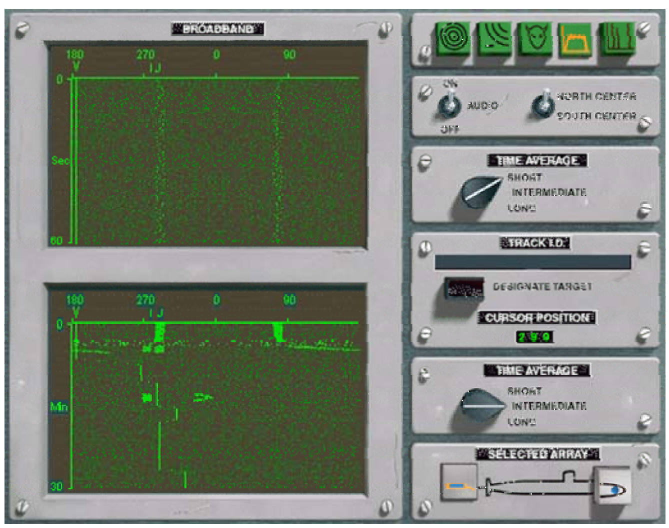

Figure 3. An example of an ASVDU taken from Jane’s 688i game for the personal computer.

b. Combat Control System

The Combat Control System (CCS) display has a single contact panel that is used for solution generation by the Fire Control Technician of the Watch (FTOW). The CCS display system has been updated recently. Most submarine's CCS displays are monochromic. The updated displays are color. The panel can be displayed on any of the four CCS display consoles. However, a contact that is displayed on one console in this panel may not be displayed on another console. This prevents two operators from working on the same contact solution at the same time.

The CCS single contact display panel is a powerful tool for the watch team. It aids the operator with the development of contact solutions. Other than the contact solution the operator is responsible to develop, the panel also displays calculated information to the operator. Bearing rate, time spent collecting data and the closest point of approach are available to view from the computer.

Operators use the CCS displays for all levels of SA. The CCS individual contact panel displays basic information such as contact bearing. In addition, the panel displays information to support comprehension of the situation such as range, classification, and angle on the bow. The panel's predictive data based on the solution the operator builds from the low-level data, support Level 3 SA. Examples of predictive data include, the contact's closest point of approach, and the bearing and time at which it will occur.

c. Commanding Officer's Tactical Display

The Commanding Officer's Tactical Display (COTD) is another panel that is available on one of the four CCS display consoles. The COTD does not have an operator. Instead, its function is to display all the CCS contact solutions in a top-down 2D display with ownship in the center. It is available for

the OOD to aid in building his mental model of the environment, determine the validity of the contact solutions in CCS, and provide the FTOW with SA of all tracked contacts.

The COTD supports Level 2 SA. The top-down display provides a comprehension of the contact environment. The user can use this comprehension to build mental models and predict future events, but the COTD does not provide Level 3 SA.

d. Geographic Plot

The Geographic plot (Geo Plot) is a large paper and pencil display that sits on a horizontal table in control. An operator (plotter) updates the Geo Plot regularly. The plotter draws bearings to contacts and generates solutions based on the bearings. The plotter passes the solutions written on paper to the Junior officer of the Watch (JOOW) or OOD for evaluation.

The Geo Plot is the primary display used to share the OOD's mental model in control. The large size makes it easy for personnel to gather around and see the contact picture. Color is used systematically on the plot to identify features such as ownship, shipping lanes, primary contacts and secondary contacts. In addition, any information can be drawn on the plot. It is common to have aggregated contact information drawn in the location of the contact.

The Geo Plot has been incorporated as a digital display in updated CCSs. Plotters still operate the display on a CCS panel. The information is passed electronically in the updated systems.

Level 3 SA is achievable using the Geo Plot. After determining a contact's range, course and speed, the plotter can easily forecast the future by extending the course line and labeling the line with future times. The OOD often uses this plot feature to make decisions.

e. Contact Evaluation Plot

The Contact Evaluation Plot (CEP) is another pencil and paper plot in control that is operated by a plotter. Its positioned vertically like an easel. The display integrates ship's heading with each contact's bearing over time. True bearing is the horizontal component and time is the vertical component. The results of the display have a "waterfall" aspect much like the ASVDU. However, the plotter only records the bearings of contacts tracked. Therefore, the display is cleaner than the ASVDU (especially when many contacts are tracked), and a record is maintained of all tracked contacts. The CEP satisfies Level 1 SA. The plotter receives bearing information for all contacts over the phone. Each contact is normally drawn with a different color pen to identify the contact traces easier.

The CEP has significant value for an after action review (AAR). It is common practice is to perform an AAR after critical evolutions. Since ships headings, contact bearing information and status briefs conducted by the OOD are required information on the plot, it serves as the primary tool to reconstruct the events for AAR.

The CEP has also been incorporated as a digital display in recent updates to the CCS. However, the designers have changed the name to the Fusion Plot because the new display automatically overlays the information described above on top of raw sonar information. The effect is a much more distinguishable sonar trace.

2. The Control Room Watch Team

Submarine control rooms are routinely manned by a watch team. Operators that interact with computer systems and supervisors that direct their operations and make decisions comprise the submarine control room watch team. During operations when a heightened state of alert is required, the Commanding Officer (CO) will mandate that the Section Tracking Party (STP) to

be stationed in control. Additional operators and supervisors join the watch team for purposes mostly to aid in contact solution development and decision-making.

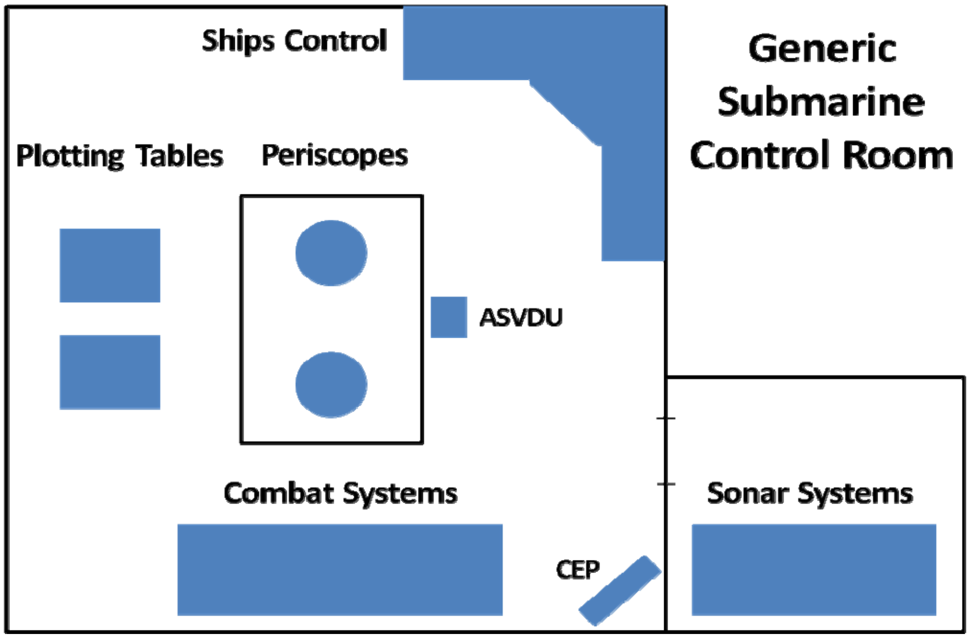

Figure 4. Generic Submarine Controlroom (shaded items are panels displaying information).

The submarine control room watch team is responsible for coordinating and maintaining safety of ship during evolutions that require complex problem solving. Safe ship handling is a team endeavor. The operational environment is rugged and complex. Submarines use sensors to collect data about the ship's environment. During normal submerged operations, the watch team's primary sensor is passive sonar. Operators monitor sonar displays to gather real-time data. An experienced supervisor guides these operators to ensure proper data collection. The supervisor passes the information to the OOD and other operators using communication channels or making the information available on displays. The team of operators and supervisors support the decision making process owned by the OOD.

Team Member	***Responsibility***
Officer of the Deck (OOD)	Manages and leads watch team – key decision maker
Junior Officer of the Deck (JOOD)*	Generates solution to contact of interest (COI)
Junior Officer of the Watch (JOOW)*	Coordinates all contact solutions from sources other than combat systems
Sonar Supervisor (Sonar)	Detect, track and classify contacts received on Sonar system and single sonar communicator to OOD.
Geoplot (GEO)*	Maintains a pencil and paper geographic display of physical constraints and contact solutions.
Contact Evaluation Plot (CEP)/ Fusion Plot	Maintains a pencil and paper graph of time versus bearing. Also, records control room communications on the same graph. Provides graphical record of ship's maneuvers and contacts' position. Fusion plot is electronic version available on newer ships or ships recently upgraded.
Time Frequency Plot (Time Freq)*	Maintains a graph of time versus frequency. Aids in developing solution of any COI.
Time Range*	Maintains a graph of time versus estimated contact range. Aids in developing solution of any COI.
Time Bearing*	Maintains a pencil and paper chart of time and contact bearing. Aids in developing solution of any COI.

Table 1. Chart identifying the Section Tracking Party members and their responsibilities. Members identified with an asterisk (*) are additional party members not normally stationed in control.

3. Real-time Environment

The information collected about the environment is processed real-time. Information collected from passive broadband sonar system is displayed to the operator. The operator scans a waterfall display (noise level on a bearing line relative to the ship's heading displayed over time) for new contacts. When the operator gains a new contact, he reports to the Sonar Supervisor within seconds after assigning an automatic tracker. The Combat Control System (CCS) receives the information from sonar directly. The Fire Control Technician of the Watch (FTOW) analyzes the information to develop contact solutions in near real-time. The span from data source to solution generation can be measured in seconds.

4. Complex Environment

An ocean environment is complex. The ocean can change rapidly and therefore cause severe changes in noise propagation and ship control. A change in water temperature can affect ship's operation and tracking ability by changing the density of the water. Changes in the way sonar receives sounds signals can make the problem of solving tracked contacts very difficult. Some changes to the ocean environment are predictable based on physics. These environmental changes are incorporated into calculations to better approximate detection capabilities and ship handling. Other changes are based on weather, which is significantly less predictable. The complexity of the submarine environment makes the task of safe ship handling for the control room watch team difficult.

5. The Periscope Depth Evolution

Many situations can overload a control room watch team with information and procedures to make proper decisions for safe ship handling. A common task for a submarine watch team is to come to periscope depth (PD) from normal operating depth. During the PD evolution (an evolution for submariners is a set of tasks that when completed alters the state of the system), sensors gather information about surrounding noise emitted from surrounding vessels, referred to by submariners as a 'contact.' System operators, with the aid of computers, then manipulate the information to determine the range, course and speed. This process is referred to as 'generating contact solutions'. The watch officer uses the contact solutions to make an informed choice on the heading on which to take the ship to PD. The CO reviews the OOD's assessment by comparing the generated solutions against raw data visible on the ASVDU (Auxiliary Sonar Visual Display Unit). The ASVDU is a repeater of selected sonar system functional displays. If the OODs assessment is safe, the CO gives the OOD permission to make the assent to PD.

Several procedures are available to aid the watch team to successful completion of the PD evolution. The Commanding Officer Standing Orders

(COSO) are several pages of guidance for the evolution available to the watch officer for reference. There are also Operating Procedures that the watch officer must follow to ensure the safe ascent to PD. The COSOs are specific to the each CO. The OPs are specific to a class of submarine. The watch team must strictly follow these procedures. For some evolutions, the submarine force has promoted checklists to ensure watch teams follow all guidance. However, due to the complexity of the problem (no two evolutions are ever the same), a checklist is rarely employed. In addition, there is not enough time to revisit the manual between decisions. Thus, it has become necessary for the watch team to review the PD procedure prior to conducting the evolution.

The ascent to PD is unequivocally the most stressful evolution a control room watch team can undertake other than an actual engagement. The risks are significant: collision, damaged equipment, loss of life and loss of ship are all possible outcomes. The procedures and guidance are in multiple locations. The information processing required to make safe ship handling decisions scales with the number of contacts detected and tracked. Therefore, in higher density contact situations, the decision making process can be overwhelming to even the most experienced.

C. COGNITIVE TASK ANALYSIS

A task analysis is the process of identifying specific actions a human performs to complete a task (Chipman 3). Researchers perform task analysis for many reasons, including the design of computer systems to support human work (Chipman 4). Researchers can use the process to identify actions for computer systems to automate. A task analysis can also identify requirements for any system with human interactions (Chipman 4). Cognitive task analysis is "the extension of traditional task analysis techniques to yield information about the knowledge, thought processes, and goal structures that underlie observable

task performance" (Chipman 3). Therefore, a cognitive task analysis not only identifies the physical acts performed by humans but the mental processes that are behind the acts.

D. AUGMENTED REALITY

Augmented reality (AR) is a fusion of what the user sees in the real world with computer-generated graphics in order to "augment" the user's reality with helpful information (Bimber and Raskar 2). A virtuality continuum, defined by Paul Milgram and Fumio Kushino, spans from the completely real environment to an environment completely computer-generated (virtual). AR is a part of the Milgram/Kushimo virtuality continuum.

Figure 5. Virtuality Continuum. [From Milgram and Kushino]

Researchers are conducting significant exploration in the AR field; however, very little practical application of the technology has been generated. AR permits users to gather real world information from their vision and have real-time information provided about their surroundings. This is drastically different from virtual reality (VR). A VR system immerses the user in a three-dimensional (3D) computer-generated environment (Bimber and Raskar 1). The three basic components to an AR system are displays, registration and tracking, and the application.

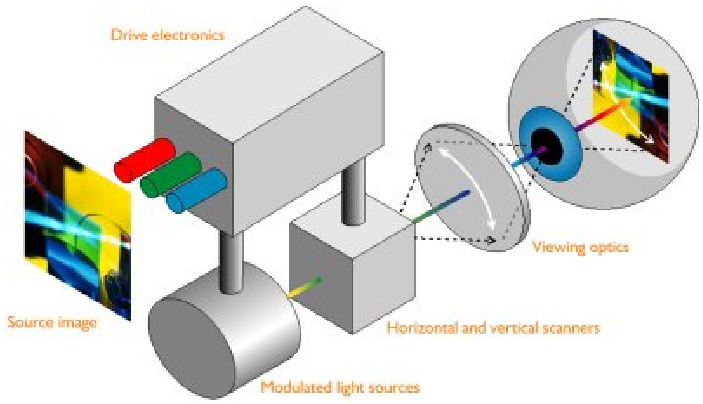

Figure 6. Virtual Retinal Display [From Capps]

Despite significant research in displays for AR systems, most wearable displays, or head-mounted displays, are still too bulky and uncomfortable to wear. AR system designers have also used cell phones, personal digital assistants (PDA) and computer monitors for AR displays (Bimber and Raskar 5). Current research in laser retinal displays (VRD) may provide a lightweight, wearable display for AR systems (see Figure 5) (Capps). Apart from the physical characteristics of the displays, the two methods used to augment a user's reality are video see-through and optical see-through. Video see-through techniques use cameras to capture the user's visual sensory and then renders the useful information into the video and then presents the video to the user in real-time (Bimber and Raskar 5). Optical see-through displays generate graphics that are on top of the user's normal visual senses (Bimber and Raskar 5).

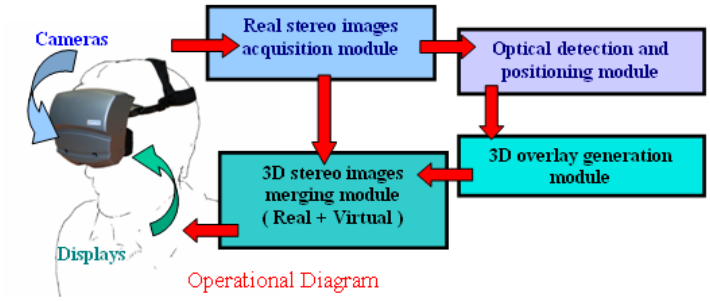

Figure 7. An Example of the Video See-Through Display Method

The tracking and registration systems used in AR systems provide orientation information about the user to the computer. Tracking and registration is the most difficult part of AR (Bimber and Raskar 4). The computer needs to monitor the location of the user and the position of the head. There are different types of tracking and registration methods. Outside-in is a method that applies fixed tracking sensors in the environment to track emitters on the AR system users (Bimber and Raskar 4). Inside-out tracking attaches the tracking sensors to the moving user and the emitters are fixed in the environment (Bimber and Raskar 4). In each of these methods there are different physical means to track a user. Tracking in AR systems can be achieved by electromagnetic sensors, optical sensors, and mechanical sensors (Bimber and Raskar 4). Outdoor AR systems have recently been developed with Global Positioning System (GPS) tracking (Bimber and Raskar 5).

III. LITERATURE REVIEW

A. INTRODUCTION

A literature review of Cognitive Task Analyses (CTA) and analyzing a system for Situational Awareness (SA) improvement was conducted. There have been a significant number of writings on CTAs. Since submarine control rooms are operated by watch teams, the focus of the literature review was on decision making by teams in complex real-time environments. One piece of literature on evaluating SA in a system to determine the use of a technology was instrumental in forming this research and is included below.

B. COGNITIVE TASK ANALYSIS OF A DECISION-MAKING TEAM IN A COMPLEX REAL-TIME ENVIRONMENT

1. Introduction

A CTA of teams operating in real-time complex environments presents difficult challenges for researchers. A traditional task analysis can rely on pure observation actions taken. Since a CTA is interested in understanding the information used to make decisions, it often requires the observer to question the user to obtain the information. This method can interfere with the user's decision making in a real-time complex environment. Therefore, I followed the steps outlined by Zachary, Ryder and Hicinbothom in their paper that addressed these issues, "Building Cognitive Task Analyses and Models of a Decision-Making Team in a Complex Real-Time Environment":

1) Perform an a priori domain analysis.

2) Define the subjects, settings and example scenarios.

3) Record the subject performance in a simulated problem solving exercise. Perform a question-answer session immediately following the simulation, using problem replay.

4) Analyze and represent the data.

2. A Priory Knowledge

It is important for an analyst to have a priori knowledge when conducting a CTA of a team operating in a real-time complex environment for two reasons. The first reason is it saves time (Zachary, *Building* 368). The analyst will have fewer elementary information exchanges with the subject. The second reason is that it establishes a rapport with the subject (Zachary, *Building* 368). A subject who spends less time answering elementary questions could be more cooperative to the analyst.

3. Subjects

Researchers should conduct cognitive task analyses with domain experts as the subjects to minimize variations in data gathered. Experts, novices and intermediate-level individuals vary widely in the amount domain knowledge. Most analysts broadly accept this assertion. However, these groups also have variations in the organization and representation of domain knowledge (Zachary, *Building* 368). Therefore, data collection from subjects with less coherent knowledge structures may lead to a greater variability in responses. Collecting data from experts in submarines would be ideal to minimize the number of subjects due to the variations. If domain experts are available for the CTA, a researcher should use five to ten subjects (Zachary, *Building* 368).

4. Scenario

A researcher should choose a scenario that captures the complexity and range of problem solving challenges that is important to the questions being researched (Zachary, *Building* 369). The subjects should encounter a representative problem in the scenario. Selecting a routine evolution in the submarine will ensure that all subjects have experience with scenario and can provide responses to the questions. The scenario should be chosen so that the problems are encountered in a natural environment. This will allow the subjects

to respond to the challenges naturally. The researcher will gain a higher quality of data from the subjects if these scenario goals are met and therefore require fewer subjects.

C. HUMAN PERFORMANCE EFFECTS OF ADAPTIVE AUTOMATION OF VARIOUS AIR TRAFFIC CONTROL INFORMATION PROCESSING FUNCTIONS

1. Introduction

In Christopher McClernon's research, the author analyzes the impact of automation on SA in the Air Traffic Controller (ATC) domain. Although the domain and technology are different, the research is very similar. McClernon sought to measure the influence a technology (Automation) had on operator SA in ATC.

2. Methodology

McClernon first identified the common tasks of an ATC and assigned a Level of SA achieved for each task. Using a simulation, the author empirically measured the Level of SA achieved for each action for a group of study participants using a system called SAGAT (Situational Awareness Global Assessment Technique). The experiment measured the effects of automation on SA.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. METHODOLOGY

A. INTRODUCTION

I required a method to answer my first four research questions. Specifically, the method would need to identify what information and its sources are required by OODs to make prompt decisions in the control room and if any communications are required to retrieve this information. I selected to conduct a cognitive task analysis (CTA) on a control room watch team to answer those questions. A CTA identifies the tasks completed in a process and the reason for conducting the task. After conducting a literature review to determine the correct process for the CTA, I proceeded with setting up for the experiment in the manner described in the sections that follow.

B. SCENARIO DEVELOPMENT

For the required research to answer the questions about critical information and its sources, I would have to observe the target subjects interacting with displays and holding communications with the other team members. The research also required that the scenario have a complexity that would force the subjects to view many of the control room displays. The scenario also needed to be routine enough so that my findings would be considered relevant. Drawing from my experience, I knew that one evolution in particular met these requirements. I selected a high contact-density periscope depth evolution from normal operating depth as the scenario to evaluate a CTA. The contact management segment of the evolution requires significant knowledge retrieved through display use and communication. This procedure is conducted routinely; often times the evolution is conducted every watch[1] while at sea.

[1] A normal watch is six hours on a submarine.

Knowing which evolution to observe, I then determined to control the scenario with respect to time-of-day and watch team makeup. The first control I implemented was that the evolution would be conducted during daylight. The complexities of visual contact management grow when the evolutions is conducted during nighttime conditions. The lights are turned off in the control room during nighttime PD evolutions to aid the periscope operator while viewing the outside dark environment. Since my focus was essentially determining the OODs required information and the information sources, an unlit control room would limit my ability to observe my subjects monitoring their displays. The last restriction was watch team party make up. A control room watch team can be as few as ten (normal watchbill[2] including Sonar) and as many as fifteen when the Section Tracking Party (STP) is stationed (see Table 1). Although the STP is often stationed to help manage contacts because of the increase of experienced personnel stationed in control, an unintended detriment is that communication required to maintain team SA increases. I sought to capture the communication complexity, because from my experience the STP is often used during complex contact management evolutions such as the high-density contact PD evolution.

1. Dialogue Creation

In order to elucidate the possible watch team tasks, I first generated a dialogue of key watch team members during the contact management phase of the PD evolution. I have included a short segment of that dialog in Table 2.

[2] A watchbill is an official document that states which stations are required to be manned and the personnel assigned to each station.

Station	Dialogue	Comm Form
Sonar Operator	"Sonar Supervisor, I have a new DIMUS trace bearing 090."	Verbal
Sonar Supervisor	"Broadband, assign tracker Alpha to DIMUS trace bearing 090. Designate S-10."	Verbal
Sonar Supervisor	"Conn, Sonar, hold new DIMUS trace bearing 090, designated S-10, tracker A assigned."	Open Microphone
OOD	"Sonar, Conn, Aye."	Open Microphone
OOD	"Attention in the tracking party, S-10 is the contact of interest, track S-10. Carry on."	Verbal
Sonar Supervisor	"Conn, Sonar, S-10 is classified a merchant, on a 1-4 blade screw, making 110 shaft rpm."	Open Microphone
OOD	"Sonar, Conn, Aye."	Open Microphone
OOD	"Attention in the tracking party, S-10 is a merchant on a 1-4 blade screw making 110 shaft rpm. Carry on."	Verbal
OOD	"Attention in control. My intentions are to come right to bearing 150 to conduct baffle clear and conduct TMA on S-10. Carry on."	Verbal
OOD	"Helm, right 15 degree rudder, steady on course 150."	Verbal
Helm	"Right 15 degree rudder, steady on course 150, aye, sir."	Verbal
Helm	"OOD, Passing 090 to the right, sir."	Verbal
OOD	"Very well, helm."	Verbal
Helm	"OOD, steady on course 150, sir."	Verbal
Sonar Supervisor	"Conn, Sonar, after careful search, Sonar hold the following contacts: S-10 Bearing 078, classified Merchant."	Open Microphone
OOD	"Sonar, Conn, aye."	Open Microphone
OOD	"Fire control, report when you have sufficient data for this leg on S-10."	Verbal
Fire Control	"Report when I have sufficient data on this leg for S-10, aye, sir."	Verbal
OOD	"All stations, provide an initial solution for S-10."	Verbal
Geo	Initial solution to JOOTW	Chit
Fire Control	Initial solution entered in Fire Control	Electronic
CEP	Initial solution to JOOTW	Chit
JOOTW	Initial solutions to JOOD and OOD	Chit

Table 2. An example of communications during the contact management segment of the PD evolution.

2. High-level Procedure

I then constructed a high-level procedure to use as a guide for the observation and collection phase of my research. The procedure starts with preparation items such as reviewing procedures and briefing supervisors and ends with correlating visual contacts with sonar contacts. The procedure is listed in Table 3. It is low detail, but it would provide a guideline to direct my observations of the subjects.

1) Line up the periscopes and ESM early warning device.
2) Brief all supervisors.
3) All personnel take stations.
4) Change depth to depth consistent with surface layer.
5) Change speed to speed to sonar search speed.
6) Conduct a baffle clear.
7) If sonar detects and tracks new contact(s),
    a. gather sufficient sonar information on contact(s),
    b. go to step 5.
8) If each contact does NOT have 2 or more legs of data,
    a. Gather sufficient sonar information on contact(s).
9) Analyze safe course for PD.
10) Inform Sonar Supervisor of selection of PD course.
11) If Sonar Supervisor does NOT concur with PD course,
    a. go to step 9.
12) Change course to PD course.
13) Change speed to speed required for PD.
14) Brief and obtain permission from CO.
15) If CO does NOT concur with PD course,
    a. go to step 9.
16) When speed is slower than speed limit to raise scope, raise scope.
17) Observe environment through scope.
18) Order Dive to proceed to PD.
19) Listen for auditory cue from ESM early warning device.
20) Using the periscope, scan for close contacts.
21) If close contacts exist
    a. announce, “Emergency deep.”
    b. Lower periscope.
    c. go to step 9.
22) If safe to maintain ship at PD,
    a. correlate sonar contacts with visual contacts.

Table 3. Periscope depth evolution procedure developed to guide the observation and question portion of the research.

C. SUBJECT DETERMINATION

A control room watch team of domain experts would include highly trained, and the most experienced operators and supervisors. A submarine CO, with more than sixteen years of submarine service and more than 20 months of training, is the obvious domain expert for the positions normally staffed by submarine officers. The CO is the domain expert for the OOD, Junior Officer of

the Deck (JOOD) and Junior Officer of the Watch (JOOW) positions. Enlisted personnel normally man the other positions listed in Table 1 and are considered the domain experts in those positions.

D. COLLECTION ENVIRONMENT

I chose to conduct my research at the Submarine Multi-Mission Team Trainer (SMMTT) located in the Naval Submarine School based on several reasons. First reason was the accessibility of the facility. I possess the security clearance that allows me to enter the facility. The second reason is the availability of subjects. Naval Submarine School staff instructors train and evaluate SOAC students in the SMMTT each week. The fourth reason for selecting the SMMTT as the setting for my study is that it is a realistic simulated control room environment. The SMMTT contains the actual combat and sonar system displays that watch teams use in the actual submarine control room. The test environment includes use of a simulated periscope. In the SMMTT, staff evaluators operate computer-based simulators to create sensor information that is displayed as real-time data on interfaces that are identical to those used on actual submarines. The final reason for selecting the SMMTT as the collection environment was that I could meet the controls that I established in the scenario development phase of my methodology. The SMMTT was able to support daytime operations and a STP was available for watchstanding.

E. RECORD SUBJECT PERFORMANCE AND ELICIT INFORMATION

1. Observation

At the SMMTT, I had access to junior submarine officers whom I considered intermediate-level subjects. The subjects were attending Submarine Officer Advanced Course at the Naval Submarine School, in Groton, Connecticut. These officers were preparing to return to a submarine in a department head capacity. They all had varying levels of experience as an OOD

during their first sea duty assignment on a submarine. Although the subjects had considerable experience and several months training, I could not consider them experts in the domain. Thus, since I could not categorize my subjects as experts, I observed above the normally suggested five to ten subjects and interviewed twelve. My previous knowledge aided in data collection. I was easily able to speak with the subjects to gain knowledge of their decision-making process. My questions were to the point and the subjects' displayed complete cooperation with me.

A disadvantage of conducting the research under these conditions was that control room operators were not domain experts. My intention for the research was to observe and record all communications and display use in support of the PD evolution. Combat and sonar system operators are normally trained enlisted petty officers. However, the subjects during the recorded sessions were junior officers. Officers have training for the operator positions and experience in operating the systems. I do not consider the officers that operated the systems as expert operators. This impacted my research minimally since all operators were trained on their displays. However, response times for information queries by the OOD were slower than I observed in my experiences standing OOD with expert users operating the displays.

2. Questioning

While observing the subjects and recording the data, I identified the tasks completed by the OOD. I specifically identified the times the OOD sought information from a display or requested information from an operator. After the watch team conducted the PD evolution, the supervisors operating the SMMTT call for an after action review[3]. It was during this process where I conducted my questioning to determine the reasons behind the completed tasks. During the questioning phase of my research, I asked the OODs to provide the reason why

[3] An after action review is common in the military. It is a review of the process, conducted by supervisors, in order to identify lessons learned from actions taken.

displays were analyzed and why identified information was requested. I was also interested in determining if there was any information the OOD thought was missing during critical times of the evolution. I asked the subjects questions that supported my research goals like the following:

- “When making the decision to conduct a baffle clear to the left, you looked at the ASVDU. What were you looking for?”
- “During the visual correlation of sonar contacts at PD, what information were you missing?”
- “When you gave the order to update all solutions to the JOOD, what was the desired outcome and why did you order it?”
- “During your baffle clears, how were you able to determine the number of legs you had on each contact?”
- “After completing a baffle clear, sonar reported you had gained a new contact. How did you know it was a new contact and not a regain of an old contact?”
- “During your data collection phase on ____ contact, how did you know how long you were collecting data on each contact?”
- “When selecting a course for PD, you looked at the ASVDU. What were you looking for?”

F. ASSIGN A LEVEL OF SA FOR EACH TASK

Each task in the CTA that involved information or information flow is related to situational awareness (SA). It was necessary to determine the Level of SA affected by each task as well. A table was composed of all the tasks and the Level of SA associated with each task. That table is located in Appendix D.

G. SUMMARY

Using my prior experience and information gathered during my literature review, I set up and ran an experiment that provided the research data that would enable me to answer my questions. I selected a complex scenario that allowed me to capture the information necessary to answer my first four research questions. I collected the information in a simulated environment, which gave the

advantages of easy access to the subjects and a questioning period that was acceptable for research and fit the subject's busy schedules. A disadvantage of the simulated environment was that submarine domain experts (COs) were not available for observation. However, by increasing the number of observations of intermediate-level expertise users I was able to record sufficient data for analysis.

V. RESULTS

A. INTRODUCTION

In this chapter, I cover the results of conducting the cognitive task analysis (CTA) and the analysis of those results. The CTA of the periscope depth (PD) evolution, along with answering the first four research questions, provides the basis on which I build my case for improving the control room display systems onboard submarines. Two specific weaknesses are identified in the display system that, when replaced with a proposed new display technology, may lead to improved situational awareness (SA) by control room watch teams.

B. COMMUNICATION DURING THE PERISCOPE DEPTH EVOLUTION

Communication in control was monitored and recorded during the observations of the PD evolution. Communication other than that noted in the CTA occurred in control during the observations. Most of the communication that occurred supported building and maintaining a shared picture of the environment. Common communication that was not initiated by the OOD was the question, "what is your solution for this contact?" Other communication that was recorded during the observations, that was not always in response to the inquiry for a solution, was "here is my solution for the contact." This communication was achieved in two ways. It was passed either verbally or by a written chit.[4] The observed verbal communications are represented in Figure 11. The written communication is detailed in Figure 12.

[4] *Chit* is a term used to describe a paper form used by the U.S. Navy.

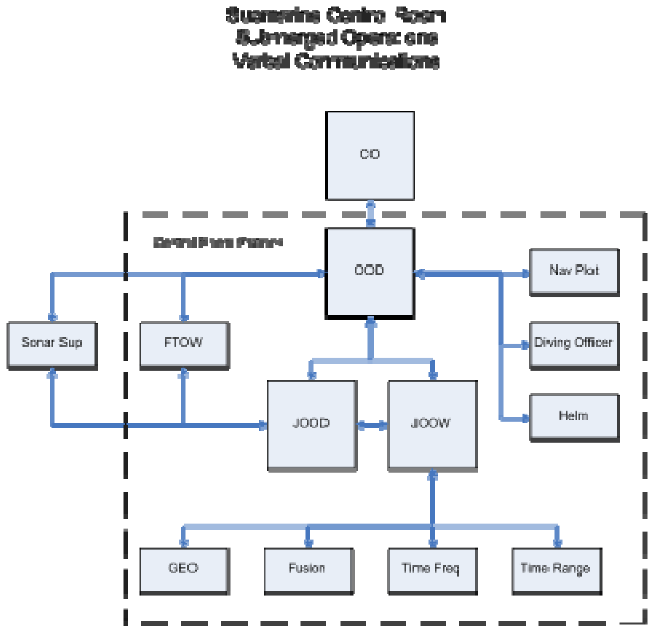

Figure 8. A flow chart of submarine control room verbal communications during normal submerged operations.

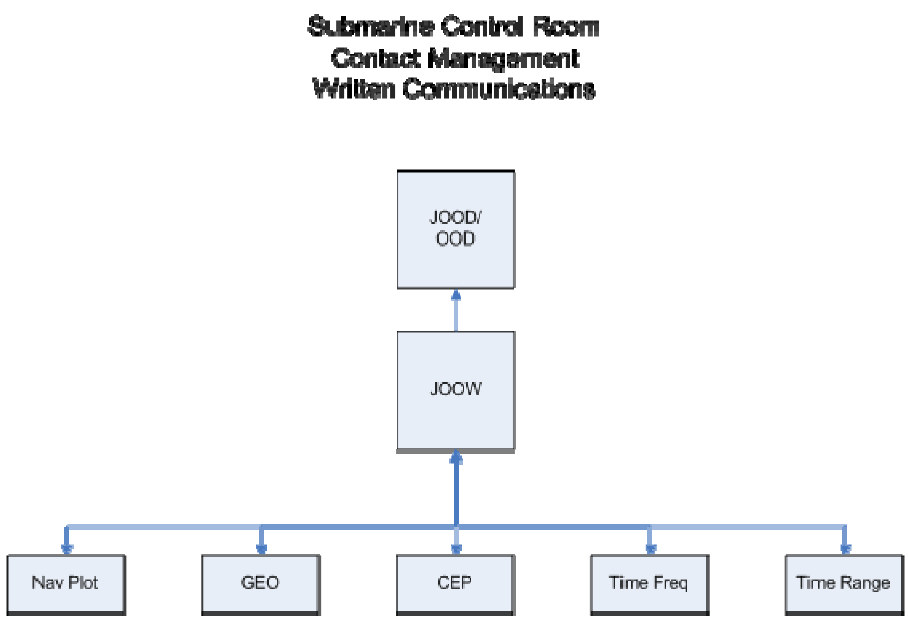

Figure 9. A flow chart of submarine control room written communications that occur during contact management.

C. COGNITIVE TASK ANALYSIS STRUCTURE

The CTA is organized to detail the communication that occurs during each task. In order to accomplish this, each task identified in the high-level procedure is separated into subtasks. The subtask is identified and assigned an originator, a receiver, type, mode, result. The CTA documented any retrieved knowledge structures or cognitive reasoning in the final column for each recorded task.

The CTA distinguished between six different types of communication. The types of communication labels were altered after the experiment to include *Calculation*. It became obvious that the original types would not sufficiently describe the cognitive load that was occurring on some of the classified tasks that cannot to be discussed in detail. The full list of communication types used in the research is recorded in Table 4.

Title	Role
Calculation	The originator performs a calculation for development of information of a higher level of abstraction.
Directive	An order is given by the originator for the receiver to perform a task.
Operation	The originator (a human) interfaces with the receiver (a system) to perform a function.
Query	The originator seeks to gain information from the receiver. If the receiver is blank, then the receiver is the originator.
Status	The originator is providing information to the receiver.
Warning	The originator is providing an alert to the receiver that requires immediate attention.

Table 4. List of communication types used in the Cognitive Task Analysis.

The mode of communication list remained constant through the experiment. There were for modes of communication. The cognitive mode is used to identify querying of stored cognitive knowledge as well as the calculations that occur during the classified steps. A full list of communication modes are provided in Table 5.

Title	Role
Auditory	Information is received by the ears.
Cognitive	The originator is internally communicating.
Manual	The originator is passing information with his hands.
Visual	Information is received by the eyes.

Table 5. List of communication modes in the Cognitive Task Analysis

Each CTA subtask has been assigned an originator and a receiver. An originator is a watch team member that conducts the subtask. The most common originator is the OOD. This is an expected outcome due to the key role in the decision-making process the OOD assumes. Most orders originate from him. The receiver identified in a subtask is a person or system that is in receipt of the communication. A common receiver was once again the OOD. Most information flows to the OOD for making decisions. A full list of originators and receiver that were identified during the study are located in Tables 6 and 7. The lists are separated to distinguish personnel from systems.

Title	Role
ASVDU	Auxiliary Sonar Visual Display Unit – a repeater display in control for the OOD and JOOD to monitor sonar traces.
CCS	Combat Control System – a generic title used to describe the fire control computer systems used to track contacts. Operated by the FTOW.
COTD	Commanding Officer Tactical Display – a panel in the CCS that provides a top-down 2D, ownship-centric display of all contacts and their system solutions.
Fusion	Fusion Plot – a panel in the CCS that provides a display of contact bearings over time. An electronic plot that is on some ships. Older ships use the paper and pencil Contact Evaluation Plot.
Geo	Geographic Plot – a manual paper and pencil plot that records contact bearings and develops independent contact solutions.
Nav	Navigation Plot – a manual paper and pencil plot that maintains position of the ship. Operated by the Quartermaster of the Watch.
SSP	Ships Status Panel – a panel that displays speed, course and depth. There are usually three displays in control (depending on class of ship).

Table 6. List of systems identified as originators and receivers in the CTA.

Title	Role
All	All control room watch team members
FTOW	Fire Control Technician of the Watch – operates the Combat Control System
Helm	Helm – steers the submarine using the rudder on direction of the OOD
JOOD	Junior Officer of the Deck – stationed under the OOD when the Section Tracking Party is set in control. Directs the contact management portion of safe ship handling.
OOD	Officer of the Deck – reports directly to the CO and is directly responsible for the safety of the ship and executing the orders given by the CO.
Sonar	Sonar Supervisor – supervises the sonar system operators and reports directly to the OOD for safety of the ship.

Table 7. List of personnel identified as originators and receivers in the CTA.

The data is organized into segments to enable easier analysis. The first segment of the CTA is the Preparation Segment. In the first segment, the watch team performs the tasks that enable them to conduct the evolution safely, such as reviewing procedures, briefing the current environment and setting the ship in the depth stratum to monitor for surface ship sound emissions. The second segment records the tasks of determining the contact situation and obtaining permission from the CO for the ship to ascend to PD. This segment is the Contact Management Segment. The Ascent Segment is the last portion of the CTA. It details the tasks of ascending to PD and the contact correlation phase that occurs once the ship is safely operating at PD.

1. The Preparation Segment

The Preparation Segment involves the tasks that in whole do just what the title suggests, prepares the watch team for the evolution up to the beginning of the contact management phase of the evolution. The starting point was selected as the point at which the OOD decides to conduct the evolution. In practical terms, either this will be on direction from the CO directly by verbal communications or by the CO's written orders directing a task completion on the OOD's watch. The endpoint of this segment is when the ship is in a state to commence the sonar data collection phase for the next analysis segment: the Contact Management Segment. The high-level procedural flow chart for the Preparation Segment is provided in Figure 10. The Preparation Segment CTA is included as Appendix A.

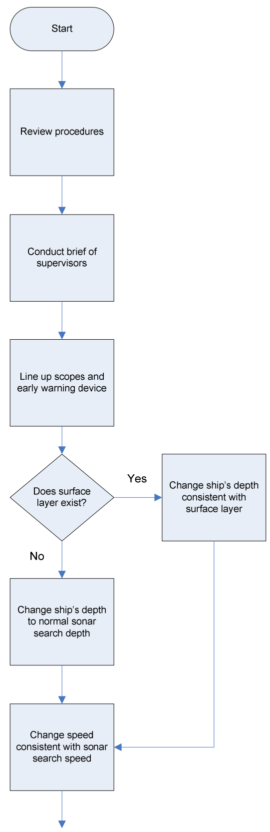

Figure 10. The Preparation Segment High-level Procedural Flow Chart of the Periscope Depth Evolution.

2. Contact Management Segment

The Contact Management Segment one of the most cognitively intense portions of the PD evolution. In this segment, the watch team maneuvers the ship to check if sonar contacts are in areas around the ship that sonar is unable to detect for various reasons. Since, "single-leg" solutions offer no reliability of actual contact information, additional "legs" are required to gather information from sonar for use in the combat control system. The fire control operator uses this accumulated information to build an accurate system solution for each contact. The analysis segment is finished when the CO gives the OOD permission to proceed to PD on a safe course selected by the watch team. The CTA of the Contact Management Segment is included as Appendix B.

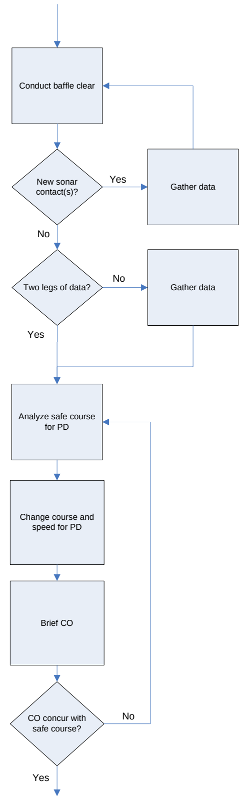

Figure 11. The Contact Management Segment High-level Procedural Flow Chart of the Periscope Depth Evolution.

3. Ascent Segment

The ascent to PD is suspenseful period in the control room of a submarine. All personnel are required to remain quiet until the OOD finishes the search for close contacts to ensure the ship's safety. The Ascent Segment starts when the periscope is raised and tested and is finished after the OOD has correlated the sonar contacts with the visual contacts. Correlating visual contacts and sonar contacts is a communication-intense activity. Figure 12 displays the overall procedural flow chart of the Ascent Segment of my analysis. The Ascent Segment CTA is included as Appendix C.

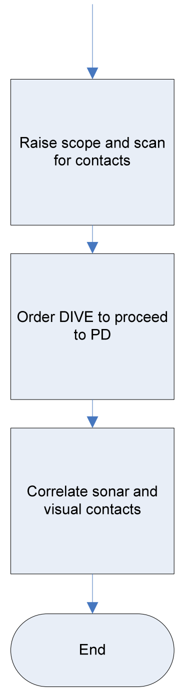

Figure 12. The Contact Management Segment High-level Procedural Flow Chart of the Periscope Depth Evolution.

D. A STEP OF THE COGNITIVE TASK ANALYSIS IN DETAIL

Due to the size of the CTA, only one analysis of a single significant step of the Contact Management Segment is included in this section. The first step in the top-level procedure is *Conduct a baffle clear*. The CTA separates the tasks necessary to satisfactorily conduct this step of the procedure. The tasks are identified in Appendix B.

1. Determining Current Contact Situation

The first subtask in this step is to *Determine current contact situation.* This goal of this subtask is to have a stored mental model of all contacts currently tracked to the accuracy available to each contact. There were three observed methods that OODs chose to complete this task and thus identified on the CTA with a SELECT statement.

a. *Building a Mental Model of a Contact*

Some OODs chose to conduct the first option, *Build mental model of contacts.* This subtask was accomplished for each contact and therefore is identified with a FOR EACH statement. The OOD was observed building a mental model of each contact by accomplishing the following steps:

- Observe and store the contact bearing on the ASVDU,
- Determine the contacts bearing rate.

The final subtask of determining the contact bearing rate was accomplished three different ways and therefore identified with a SELECT statement. The following were the observed choices:

- User experience,
- Short duration calculation,
- Or, requesting the bearing rate from the FTOW who retrieves the information from a panel.

User experience is a step chosen by experienced OODs that train their eye to determine approximate contact bearing rate. It was often observed that when building a mental model, it is acceptable to be inaccurate to an allowable tolerance. Acceptable contact model accuracy can vary depending on the classification of the contact and context of the situation. The accuracy of acceptable contact solutions is not relevant. OODs learn to estimate a contact's bearing rate by observing the trace generated by a contact on the ASVDU and then viewing the contact's instantaneous bearing rate available on the CCS display. The OOD then categorizes observable bearing rates that require action such as:

- zero bearing rate (a constant zero bearing rate over a long period is a potential collision hazard),
- 0-3 degrees per minute (no special interest),
- >3 degrees per minutes (a potential close contact).

An important point is that in this subtask, the user is required to have training and experience to gain sufficient Level 1 SA.

Calculating a bearing rate for a contact is a simple math calculation that can be accomplished quickly and was observed during the experiment. It is identified on the CTA as a *Short duration calculation*. The OOD identifies a period of time that bearings are visible on the ASVDU and then takes the difference between the highest and lowest bearings observed during the times. This difference is then divided by the observed time to determine bearing rate in minutes.

This optional subtask requires the user to perform a calculation to achieve Level 1 SA. This option is more often selected than the next option because it is an independent task.

The last method observed to retrieve bearing rate for a contact was a request to the FTOW for the system calculated rate. The bearing rate retrieved by the system is more accurate than the previous options. Although it was observed by a few OODs, the subjects indicated that they were reluctant to request information from the FTOW because of the detriment to the FTOW's tasks. The OODs were concerned that an interruption for basic data would adversely affect the FTOW's subgoals such as contact solution updates.

This less frequently used option of determining bearing rate is less load to the user's cognitive resources, however, requires the user to outsource the task to a team member. When this option is selected, communication is required to attain Level 1 SA.

The final subtask the OOD accomplishes when building a mental model of a contact, is *Apply best speed*. This step is cognitively intense if classification data is available for the contact. If there is classification data available, the OOD can recall the speed associated with the contact class. For example, a speed commonly used for contacts classified as a merchant ship is sixteen knots. The OOD is trained to use contact's bearing, bearing rate and speed to determine its range. An inaccurate, but acceptable, mental model is now available.

This step is Level 2 SA. Recalling contact speed information based on classification is using Level 1 SA to determine the contact situation. Putting the contact information, although is a high cognitive load, is fulfilling Level 2 SA as well.

b. Check the Top-down Display

Another action the OOD chose to complete the *Determine the contact situation* subtask was checking a 2D top-down display and is identified on the CTA as *Check top-down display*. The Geographic Plot and Commanding Officer's Tactical Display (COTD) was commonly used when this option was selected. The vicinity to the OOD and ASVDU was reportedly the reason. When questioned why the OODs selected one display over the other, they identified three reasons:

- the vicinity to their current location,
- a preference based on experience, and
- a desire to check more sources.

c. "Report All Contacts"

Although identified as a selection of options, this subtask is often used by OODs to back up the Sonar Supervisor to provide procedurally required information on each leg of data. Sonar reports on the open microphone the status of all contacts to include, bearing, tracker information, and classification. The OOD then uses the requested information to build a model.

E. RESULTS OF THE COGNITIVE TASK ANALYSIS

The CTA was conducted to identify the communication and displays viewed during a complex evolution in control. Analyzing the CTA, provides information to the research questions posed in Chapter I. A combined list of all the data gathered to answer the research questions can be found at the end of this section.

1. Information the OOD Currently Uses to Make Decisions

Identifying the information used by the OOD to make decisions provides a basic understanding of the information used by the OOD that can be used to identify an deficiencies in the display system. The CTA identified the following as the current information used by the OOD:

- contact's bearing,
- contact's bearing rate,
- contact's classification,
- contact's best speed,
- the overall contact picture,
- the validity of the overall contact picture,
- the number of legs collecting sonar data on each contact,
- the time spent on each leg collecting data for each contact,
- and ownship's course, speed and depth.

Each of the items listed above supports SA on different levels. Most of the information identified supports perception of the contacts in ownship's environment (Level 1 SA). The overall contact picture and its validity, and the classification of contacts supports understanding of the situation (Level 2 SA). None of the steps in the CTA identifies information used by the OOD to support Level 3 SA. This is a noted deficiency of the CTA. There is information displayed in control that assists the OOD with making contact predictions based on Level 1 and Level 2 SA information. The information was either not used or not recorded during the observations. This information is available on the Commanding Officer's Tactical Display (COTD) and Geographic Plot and discussed in the next chapter.

2. Displays the OOD Uses to Obtain the Information

The CTA names four different displays that the OOD views to receive above information. The OOD relies mostly on the ASVDU, from which the OOD perceives a contact's bearing and can determine its bearing rate. The OOD views the COTD to determine contact picture and its validity. The SSP contains

basic ownship's status information such as speed, course and depth. The Fusion Plot was one of the choices the OOD uses to view the number of data legs for contacts.

Information	Level of SA	Display(s)
Contact's bearing	1	ASVDU
Contact's bearing rate	1	ASVDU
Overall contact picture	2	COTD
Validity of overall contact picture	2	ASVDU, COTD
Data legs on each contact	1	ASVDU, Fusion Plot
Ownship's speed	1	SSP
Ownship's depth	1	SSP
Ownship's heading	1	SSP

Table 8. A summary of information required, the Level of SA that the information addresses and its location.

3. Communication Required to Obtain the Information

During the observations the OOD communicated with the entire watch team. However, specific communication was identified as necessary to gain information. The OOD communicates with the Sonar Supervisor to gain a contact's classification and estimated speed. Communication with the Firecontrol Technician of the Watch (FTOW) is necessary to determine the time spent on each leg for each contact. This is another noted deficiency of the CTA. There is more information required by the OOD that is only attainable by communication in the control room. These examples of communication will not be identified in the thesis. However, the identification of one occurrence where communication is required to gain information provides support for this thesis.

Information	Level of SA	Communication
Contact’s estimated speed	1	Sonar Supervisor
Contact’s classification	1	Sonar Supervisor
Time collecting data on a leg	2	FTOW

Table 9. A summary of information required, the Level of SA that the information addresses and the communication required to obtain each.

F. SUMMARY

This chapter presents the resulting structure of the CTA and discusses in detail a section of the analysis that is a representative sample of the entire CTA. Additional notes on the CTA are listed in each segment’s appendix.

This chapter also identified the communication that occurs in control during the contact management portion of a PD evolution. Most of the communication occurs to support a shared picture of the contact situation.

The CTA provides answers to some of the research questions presented in this thesis. An explanation of required information and the displays and communication that exist to enable the OOD to obtain the information is also provided.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. DISCUSSION

A. INTRODUCTION

The cognitive task analysis (CTA) of the submarine periscope depth (PD) evolution in the previous chapter is used as basis for discussion on some of the deficiencies that were noted in the control room display systems. This chapter identifies the inadequacies of each display in control. Furthermore, a discussion of the deficiencies of the control room's displays as a system is discussed. This chapter also addresses the possible requirements for an improved control room display system.

B. CURRENT CONTROL ROOM DISPLAYS

1. Auxiliary Sonar Visual Display Unit Deficiencies

The primary purpose for the Auxiliary Sonar Visual Display Unit is to supply the Officer of the Deck (OOD) with the perception of contacts in the ship's environment. See Table 10 for a summary of the ASVDU deficiencies and the Level of SA affected.

Deficiency	**Description**	**Level of SA**
Size and resolution	Unable to discern multiple contacts with close but not same bearings.	Level 1 SA
Size	As number of contacts increase, display can become confusing forcing the user to choose other displays for SA.	Level 2 SA
Control	Repeater display, no control of audio pointer to view accurate bearing to a noise trace.	Level 1 SA
Labeling	Sound traces that are tracked are identified by tracker symbol. Must look in another panel for correlation of tracker identifier and contact identifier.	Level 1 SA

Table 10. Summary of the ASVDU deficiencies and the Level of SA affected.

a. The Information can be Difficult to View

Most deficiencies of the ASVDU are attributed to its size. Insights developed from personal experience and the observations submitted in the previous chapter suggest that the size of the display is too small. For example, two contacts can be tracked separately with a five to ten degree separation between the two contacts. After ownship maneuvers, because of the relative motion, these contacts may appear to merge into a single contact. This can be attributed to the small screen size and lack of resolution available to see the thin traces as separate contacts. Since, each leg presents new relative motion between ownship and the two hypothetical vessels, the contact's bearings may once again emerge separately and become tracked individually once again. This occurs regularly on a submarine. There are procedures the Sonar Supervisors follow to ensure the correct tracking occurs. However, the physical features of the display do not allow the OOD to differentiate between the two contacts. Since the waterfall display is meant to provide contact bearing history for the purpose of analyzing the contact position over time, the ASVDU becomes useless in this situation for Level 1 SA development.

Another deficiency attributed to its size is the ASVDU becomes difficult to use during high contact density environments. In conditions where there are ten or more contacts with varying noise ratios (narrow and wide trace widths), it becomes difficult to rapidly distinguish between the contacts on the display. During the study, this deficiency became evident on one occasion when the subject stated the ASVDU was confusing and moved to the Geographic Plot to "see the answer."

b. Other Minor ASVDU Deficiencies

Other minor deficiencies on the ASVDU are control and labeling. The unit is a repeater of consoles located in the Sonar space. A pointer information box displays the bearing location of the operator-controlled directional sonar receiver (referred to as a pointer). The operator uses this

pointer to direct his auditory focus (he is wearing earphones) to listen directly to the noise on the bearing that is selected. Since the OOD cannot operate the pointer, the OOD does not have access to the precise bearing of a trace unless the operator is incidentally scanning over it. Additionally, each trace has a tracker symbol, such as A or B, over the bearing axis line to indicate which tracker is assigned to the contact. The tracker symbol is the only link on the display to the sonar number that is used to identify the contact. To link the sonar trace to sonar information, the OOD is required to identify the trace with otherwise useless data, the tracker identifier.

2. Combat Control System Display Deficiencies

The Combat Control System (CCS) individual contact panel display is a powerful display for a single user to determine the solution of a single contact. The expert user, the FTOW, is trained to operate the panel to generate accurate solutions. Most of the deficiencies in the CCS panel are based on the display's intended characteristics; it is a single-person, single-purpose display. See Table 11 for a summary of the CCS display deficiencies and the Level of SA affected.

Deficiency	**Description**	**Level of SA**
Not sharable	Desirable information to build Level 1 SA, but not portable. Results in operator interruption of primary task for information retrieval.	Level 2 SA
Not viewable	Display set up forces supervisor to become operator in order to view desired information.	Level 2 SA
Not tracking required information	Missing data field, such as “data legs’ for each contact.	Level 1 SA

Table 11. Summary of the CCS Individual Contact Panel deficiencies and the Level of SA affected.

a. *The CCS Display is Designed for Single-person Use*

The information available on the CCS individual contact panel is invaluable for solution generation and Level 1 SA. Other team members often desire information from this panel. A contact's system solution is the most often requested by team members other than the OOD from this panel. The OOD desires predictive information such as the closest point of approach and the related information.

The desired Level 1 SA data is available on this panel. However, the problem is accessibility. The CCS is not portable. The panel is not able to move to all watch team members that desire information from the panel. Therefore, the information derived from using the panel is accessible by either traveling to the panel and viewing the information over the operators shoulder, or requesting the required information to be passed on a written chit. The major issue with both seemingly sufficient answers is interruption. The FTOW's primary task is to develop solutions on all contacts. Peering over the FTOW's shoulder often results in requests. The operator is constantly scanning through his contacts to determine his solution accuracy and the need for updates. Thus, if someone is seeking information from the panel, a query of information is often requested, resulting in operator distraction. Observations and personal experience suggest that in high contact density environments where contact management is a top priority, the FTOW's focus should be directed at providing solutions to contacts that are tracked. Constant interruptions can limit the FTOW's contact management capacity.

b. *The CCS Display is Designed for Single-purpose Use*

The design of the CCS panel is to display information for solution development. The panel is a technical display that requires skills to operate it. The FTOW spends months learning to operate the displays. The FTOW has twelve months of schooling required prior to reporting to the sailor's first submarine. It then takes the same sailor about three to six months to qualify

FTOW (variances depend on many reasons, including type of CCS, person's aptitude, ship's schedule, etc). The OODs are trained to operate the panel for supervisory control in this situation, but are only intermediate-level users.

OODs recognize the problems with interruptions stated in the previous section. Unfortunately, because the information the OOD finds useful is not the focal information and therefore not easily viewable with an operator in front of the panel, the OOD leaves his supervisory role to become an operator and manipulates other panels on the CCS consoles to get at the required information. This is inconsistent with acceptable control room practices. Events like this were recorded several times during the observations of this study.

Although the panel is designed for generating solutions on contacts, there are data fields missing. During the PD evolution, the OOD is often required to review each contact's trace history using the ASVDU to determine how many legs of sonar data is collected. For high-density contact evolutions, this task becomes extremely tedious for the OOD. The FTOW can use the CCS individual contact panel to scan through the available information to count each data leg as well, once again directing the FTOW's attention away from the operator's primary task.

3. Commanding Officer's Tactical Display Deficiencies

The Commanding Officer's Tactical Display (COTD) is the ideal display to satisfy Level 2 SA. The display shows all tracked contacts with solutions developed by the FTOW using the CCS (the COTD is panel in the CCS console). The ownship-centric, top-down, two-dimensional panel illustrates contacts with standard symbols to identify surfaced and submerged contacts. The sonar contact numbers are displayed close to the icon of the contact it represents for rapid discernment of contact location. Since the display is ownship-centric, the viewer can easily transfer the top-down model to his environment and carry that model mentally, making periodic returns to update and verify his model.

Unfortunately, there are systematic problems involving the display that prevent it from being used exactly as described above. Table 12 summarizes the display deficiencies of the COTD.

Deficiency	Description	Level of SA
Not trusted	Since the data is processed, i.e. not raw data, incorrect solution generation could occur. Therefore, not trusted.	Level 2 SA
Not sharable	Unable to be seen by all team members. Results in leaving stations to view information. Therefore, decreasing efficiency.	Level 2 SA
No classification icons	Icons are limited to two general categories: surfaced and submerged.	Level 3 SA

Table 12. Summary of the COTD deficiencies and the Level of SA affected.

a. The COTD is Processed Data and not Trusted

The top-down, two-dimensional COTD combines and displays all contact solutions in the CCS. Like described above, solutions are generated by the FTOW using raw data collected from sonar sensors. A solution is required to be entered upon initial detection of a contact. Therefore, an initial solution, one that is only seconds old, will only have one attribute acceptably accurate, the contact's bearing. The solution is refined after more data collection. When the Sonar Supervisor reports classification on the new contact, the FTOW can use a better speed to refine the solution. After a course change, the solution may become even more refined such that now the FTOW finds that he needs to spend only a little time managing the contact's solution. The panel does not distinguish which solutions are initial solutions from those that are refined and acceptably accurate solutions. Therefore, the OOD is conditioned to distrust the panel while making decisions. Therefore, even though this display could provide Level 2 SA, it is mostly unused for that purpose by the primary decision maker in control.

b. Other COTD Display Deficiencies.

There are other minor display deficiencies noted during the observations. The display only has two categories of icons: surfaced and submerged contact. The OOD has cognitively stored several more models associated with classification of contacts. An example used earlier was the merchant ship. The OOD makes predictive models based on the classification of a contact as a merchant ship, such as a likely constant speed and the resistance to changing course. However, even though sonar classifies a contact as a merchant, the contact is displayed on the COTD as a surface type; the OOD and other party members write down the classification and contact number on a portable, erasable board to aid with recall. This is a Level 3 SA deficiency. The problem inhibits building predictive models of the environment.

The last minor deficiency for the COTD is that it is not a sharable display. It is a panel in the CCS console. This prevents other team members from having access to Level 2 SA.

4. Geographic Plot Deficiencies

The Geographic Plot is the most commonly used plot for Level 2 SA. However, there is a significant problem with the plot. By design, the contact solution displayed on the plot is behind the problem[5]. The operator (plotter), views bearing information from a bearing repeater display for a selected contact, draws the bearing line on the paper plot and then analyzes all the contact's bearing lines using speed information for the contact solution. This process is very time consuming. Thus, it is accepted in the submarine force that the plotter can only develop and maintain solutions on approximately two contacts, depending on the plotter's proficiency. However, the plotter is still required to maintain the full contact picture on the Geographic Plot. By personal experience and experimental observations, as contact density increases, the plotter chooses

to update the plot using solutions generated in the CCS. When this occurs, the OOD is using information from a source that is not trusted, similar to the comments addressed in the COTD deficiencies. Level 2 SA is not entirely satisfied for by the Geographic Plot, but for different reasons than the COTD. Experienced OODs are familiar with the practice of updating the plot from a source that is not trusted. The experienced OOD rightfully limits his trust of the Geographic Plot and therefore weakens his Level 2 SA. The inexperienced OOD may fully trust the plot to his folly; the OOD then makes bad predictions of future events from faulty Level 2 SA.

5. Contact Evaluation Plot Deficiencies

The relatively large and visible plot is not viewable by all team members and since information passing is required, team members require the information developed by the plot. The CEP plotter is trained to use the information on the plot to determine contact solutions. The solutions are hand written on the plot at the time of the development. When the information is required to be shared, it is passed either verbally by phone or by a written chit for an accuracy review.

6. The Combined Display System

The control room's individual displays are a functional system referenced hereafter as the *combined display system*. Although it is valuable to discuss the deficiencies that exist for each display, the control room's displays collectively provide a picture to the OOD. Identifying the deficiencies of the how the displays provide a combined picture became an apparent necessity. For a summary of the combined display system's deficiencies see Table 13.

---

[5] Behind the problem is a common phrase used in submarines to describe the inadequacy of the plot. It can take up to five minutes to have a solution worth recording and passing to other stations for review.

Deficiency	Description	Level of SA
Information must be compiled from multiple displays	The OOD requires information from multiple sources to build Level 1 SA	Level 1 SA
Individual displays do not have necessary information	Each station requires information from another source.	Level 2 SA
Forces user to maintain a spatial mental model	The OOD uses basic information provided from multiple sources to mentally form a contact solution and mentally situates the contact with respect to his location.	Level 2 SA
Solution control is limited	OOD is limited in capability to control the contact solutions. The OOD becomes reactionary as he “stumbles” upon erroneous information.	Level 2 SA
Watch team back up is limited	Team members prevent the OOD from making errors by providing timely and accurate information. Current system doesn’t promote this process.	Level 2 SA

Table 13. Summary of the combined display system deficiencies and the Level of SA affected.

a. Information must be Compiled from Multiple Displays

A number of specialty displays individually provide the user with good information. The ASVDU is the display from which the OOD prefers to retrieve real bearing and estimated bearing rate. Speed information comes from the Sonar Supervisor either by classification or by other means. The COTD can provide an adequate understanding if all the contacts solutions are refined. Determining if the COTD solutions are accurate enough for predicting future events is a combination of display queries starting at the ASVDU, requesting information from the FTOW and then checking the results against the other displays. The OOD can become overwhelmed very easily at the process of determining the overall contact picture from the plentiful data that supports adequate Level 1 SA. Too many different displays provide the required information for building Level 1 SA.

b. Individual Displays do not have Necessary Information

The operators and plotters are required to share the solutions generated. The submarine force mandates and training reinforces independent solution development from the different operators. Unfortunately, the operators do not receive all the information they need to develop solutions independently. An example is the Geographic Plot. Laying down bearing lines is not enough to come up with an answer about what a contact is doing. The plotter is required to fit a course based on speed through the bearing lines. The Geographic Plot requires "best speed" data or classification data that is not viewable at the plotter's station. He requests that information verbally from another team member. This is a trivial example of the communication increase that occurs in control due to the Level 1 SA building display system deficiencies. To reinforce this deficiency, it is important to note that during the Contact Management Segment of the CTA, there are six queries initiated by the OOD requesting Level 1 SA data. "Report bearing rate data" is an example one of these queries. Each station does not have immediate access to the information required to perform its function.

c. Forces the User to Maintain a Spatial Mental Model

An important display system deficiency is that it forces the primary decision-maker to mentally maintain all or portions of the contact model. The OOD was observed reviewing basic Level 1 SA information for cognitive mental model building. The information provides contact information that is spatially oriented in the OOD's mind. The OOD was often observed pointing to a contact in the control room; signaling the location of the contact relative to the position of the OOD. Personal experience provides evidence that effective mental modeling of the contact environment is preferred by the experienced OOD. The expert maintains a layering of solutions depending on the information available. The

layers evolve as the solution become refined with more accurate information. The display system does not provide a contact model that evolves as information is gathered.

d. Solution Control is Limited

The current display system limits watch team backup in the submarine control room. For example, the OOD has to update the watch team when vital information about the environment changes or the OOD determines that the team's understanding of the problem is significantly different from his perspective. A common purpose for updating the watch team is to relay the known parameters of a contact solution. This update is meant to focus the party on the established facts, thus eliminating individual error due to contact ambiguity. Often the OOD senses this ambiguity by overhearing information requests in control. The OOD may also discover the errors manifested in individual solutions before recognizing the information ambiguity. Often the OOD is reactive to backing up the control room watch team when trying to prevent the use of ambiguous information for the development of erroneous contact solutions. An experienced OOD understands the impact of the continuing use of ambiguous information and attempts to prevent this from occurring by constantly reviewing individual solutions, which can significantly increase the team supervisor's workload.

An example of the above problem is the discovery process of an erroneous contact solution during the contact management phase of the PD evolution. The OOD builds his mental model of a contact using the ASVDU. The OOD moves to the Geographic Plot to check the overall contact picture and notices that his freshly updated mental model of the contact is different on the plot. He informs the plotter that the contact requires updating and the plot is updated.

e. Watch Team Backup is Limited

Another limitation in watch team backup with the current system is that each team member does not have access to the overall contact picture. Therefore, when the individual receives or develops accurate information that obsoletes to the overall contact picture, the operator is unaware of its importance and may not relay it to the team. This issue is normally resolved when the OOD briefs his current contact picture to the watch team, which may be later in the problem than is acceptable. It is also important to note that each update by the OOD starts with the statement "attention in control." The team members then stop their analysis and direct their attention at the OOD.

An example of this problem is the OOD update that results in an updated contact picture. An OOD determines that it is time to update the control room team of a contact that has ambiguous data. Afterward, a team member passes a chit with information on the contact that suggests the OOD's assessment is wrong. The OOD investigates the newly passed information and determines the team member to be accurate. The OOD briefs the control room again to provide another update.

7. Summary

It is important to state that each display in control is used for effective contact management in the submarine fleet today. However, the deficiencies noted for each display limits the watch team's ability to develop SA on all levels as described in the above sections. The degree to which SA is limited is unknown.

a. An Overall Breakdown of Level 2 SA

Clearly, information such as contact bearing and bearing rate are available to view in many different formats in the submarine control room. It is easy to perceive the contacts in the environment with the displays that provide

Level 1 SA. The breakdown of SA that occurs in the control room is Level 2 SA, or the comprehension of the situation. Specifically, the COTD is not used because the OOD is conditioned to dismiss the information presented on it.

b. The Current Solution to the Breakdown of SA

The submarine force has identified the complexity of passive sonar contact management and the results of display deficiencies. The lack of submarine control room SA has forced the U.S. Navy to develop mental model training systems to assist the OOD in managing contacts in his head. Training systems teach the OOD shortcut calculations that provide reasonably accurate contact solutions from basic data (i.e. bearing, bearing rate and speed) that can be obtained viewing displays that satisfy Level 1 SA, such as the ASVDU.

Although each OOD must be trained to use the calculations accurately, the process of maintaining a contact picture in one's mind is troublesome. The future submarine designers plainly need to address these deficiencies to remove the complex Level 2 SA cognitive load from the OOD, so the primary decision maker in control can focus on making predictions of future events (Level 3 SA). The following section discusses the requirement of an effective display system for the submarine control room.

C. AN IMPROVED CONTROL ROOM DISPLAY SYSTEM

This section discusses the attributes of the system that would overcome the deficiencies noted in the previous section. The solution that resolves the deficiencies identified above will:

- be shared with necessary team members,
- be a single source for all required information for all users,
- relieve the user from creating a mental model,
- be a trustworthy display,
- spatially project the perceived environmental model,
- display classification data for each classified contact,

- allow for control of the display without becoming an operator,
- and have an adequate size and resolution for precise information gathering.

A list of the required information that the OOD needs to make prompt decisions is included as Table 14.

Information	Immediately Available?	Level of SA
Contact solution: -Where the contact is -Where the contact is going -At what rate is the contact going	Yes[6]	2
Solution strength: -Time since last system update -Visual difference between raw data and solution -Amount of data collected (time) -Number of data legs -Speed data	No	2
Contact classification	No	2
Ship's speed	Yes	1
Ships' depth		1
Ship's heading		1

Table 14. List of required information to be provided by an improved control room display system and whether the information is available in the current display system. The Level of SA that the information satisfies is also provided.

1. Provide a Single Source for Level 1 Situational Awareness Data

Since SA is hierarchal, it is imperative that Level 1 SA is established. Currently, Level 1 SA is established in the submarine control room. The system users know the basic information about each contact (Level 1 SA). There are, however, two improvements identified for the current control room display system

[6] This information is available on the COTD. However, it is important to note, that the display is often not trusted for reasons previously discussed, which prevents obtaining this information.

that address Level 1 SA. First, track and display all the required information. This may seem to contradict the assertion that Level 1 SA is established, however, note the following example. The number of data legs for each contact is not tracked. The system user currently has indirect access to this information. The user is required to review data to manually count the legs to determine if the contact meets requirements. The system needs to track the contact's leg count and display it to the user.

The other improvement required to satisfy Level 1 SA is combine all the basic information on one display. Having necessary information distributed over multiple displays causes an increase in communication which can lead to a decrease in efficiency. Additionally, the user could choose to dismiss the necessary information for the sake of minimizing communication or because of complacency. Combining all the basic, necessary information about a contact on a single display will minimize communication for basic information and potentially increase efficiency and accuracy of information.

2. Improve Level 2 Situational Awareness in Control

The identified breakdown in SA in the submarine control room is at Level 2. Level 2 SA is considered to be an understanding of information that is abstracted from the surrounding environment (Level 1 SA). To satisfy Level 2 SA, the system user needs to know where each contact is located, in what direction the contact is moving and how fast it is moving in that direction, all with respect to ownship. Currently, the raw contact information, such as bearing and bearing rate, is available, but the OOD is using too much mental effort to make the information useful. Currently, the user is still determined to collect the components that are symptoms of those parameters, such as bearing rates and angles on the bow. The calculations the OOD is trained to use, forces him to search for the raw information.

The argument against this solution is that this system already exists and no one is using it now. Although this is true, the COTD does meet all the

requirements of the previous paragraph, however, an important feature must be introduced in a new system. Each contact must have a confidence rating system visually linked with its icon. Determining the best way to display this feature is out of the scope of this thesis. However, the concept needs to be clearly defined.

As identified in the COTD section above, new contacts have system solutions as well as refined solutions. The COTD does not distinguish between these two solutions. And because the OOD cannot maintain in his head the information for each contact that supports contact strength, the OOD wisely chooses to ignore the COTD as a decision making tool.

Information collected on each contact can relate the strength of the contact's solution. For example, a new contact has no information other than bearing and instantaneous bearing rate. This contact's solutions strength is the lowest and should be identified as such; possibly only displaying the bearing and bearing rate information so the user is not forced to query another source for that information. As new information is collected, the FTOW uses it to determine an updated solution for the contact. The system updates and changes the icon to identify the new information and contact strength.

This process will permit the user to maintain an individual confidence value for each contact. Therefore, enabling the user to further analyze the contact situation and make decisions based on these varying confidence levels from a single display: reducing communication, and therefore, potentially increasing efficiency in the control room.

3. Improve Level 3 Situational Awareness in Control

A deficiency noted in the previous section was the lack of display icons on the COTD that represent available classifications of contacts. The improved display system should incorporate icons that enforce visual classification of a contact. The display user needs the classification of a contact to make predictions about the contact. This feature would remove the need for the user

to maintain a personal whiteboard for tracking contacts' numbers and classifications. This feature improves Level 3 SA that is currently supported on a separate personal display.

4. Provide a Shared Contact Picture in Control

A noted deficiency was that watch team backup was limited by the current display system. The solution for this deficiency is a shared display system.

A shared display of the contact picture and the information that supports it enables proper watch team backup. The scenarios described in the previous section on system deficiencies would not occur. The OOD would not "stumble" upon ambiguous contact information being shared by the team. Instead, the OOD would immediately identify solutions that members developed from ambiguous information. For example, if the OOD noticed on the single display that the newest contact bearings separated from solution position, the OOD would address the issue with the FTOW immediately. Additionally, each watch team member would know the contact picture on which the OOD was making decisions. Then, each member would become aware that any information the member had that disagreed with the current contact picture would be highly relevant to pass to the supervisors. This process supports good watch team backup.

D. DISADVANTAGES OF THE PROPOSED DISPLAY SYSTEM

There are concerns about a shared display solution. The submarine control room has several stations, each individually working to solve contact solutions. This is an important team feature. If each solution is independent, then the decision maker can select a best solution from all candidate solutions. Therefore, this process encourages independent member analysis for better contact solution development. Introduce a shared contact picture and the idea is that all contact solutions will become the same. This is a valid concern. However, training is used often in the U.S. Navy to solve problems that cannot be

accomplished with hardware. This is a fine example where training would provide an answer. Train and reinforce the independent nature of contact development for each watch team member.

The advantages of a shared picture enforce the need for a solution to provide an environmental model approved by the OOD and made available to all team members. Additionally, training cannot provide a shared picture; the best solution is to improve the display system. An effective training system can resolve the valid concerns resulting from a shared picture that is detailed above. However, research should be conducted to determine the impact of a shared environment picture on individual solution generation.

Another apparent disadvantage of the proposed solution is that detailed information appears to be lost to gain situational awareness. Since the contact is no longer viewed as a bearing and bearing rate, but as an icon that represents the current solution, the expert may prefer to see the details. The ship's CO may prefer to analyze a contact or contact's solution based on that contact's bearing, bearing rate and estimated speed. A display system that withheld the basic contact information might provoke an expert to discontinue use of it.

The SA gained from the system again enforces the need to provide this solution. Therefore, the improved display system should provide the ability to satisfy expert users also. Providing a feature that presents the details if queried would support the need of expert users and provide the beginner or intermediate-user an increase of SA.

E. SUMMARY

This chapter identifies the deficiencies noted from the experiment observations and author's personal experience and attempts to summarize a new display system that would eliminate these deficiencies. It is important to note that the solutions are presented, but not tested. For further information on testing the solutions to eliminate the identified deficiencies, read the Future Work section of Chapter VIII.

VII. POSSIBLE SOLUTION

A. INTRODUCTION

This chapter presents implementing Augmented Reality (AR) as a candidate technology for the improved submarine control room display system. The display system solutions for improving situational awareness (SA) in control identified in the previous chapter are used as requirements to provide general software and hardware specifications of the AR system. This chapter also discusses the advantages and disadvantages of using AR as a solution.

B. AUGMENTED REALITY DISPLAY SYSTEM ON SUBMARINES

An AR display system would provide a shared, portable, spatially oriented, heads-up, single display for the control room team member. The proposed AR display system would at first supplement the existing control room display system, and then later be incorporated into the design feature of the next submarine control room. This thesis addressed the integration process until further research can validate the studies conducted in this research. The general features of the technology are the application, registration and tracking system, the human interface device and the display device.

1. The Proposed AR Software Application

The AR software application is required to gather all the required information from the existing data sources in control and display the information to the user in a useful manner. In addition, each user may have a need for the information to be displayed in a mode that supports the station's primary task.

a. Information Sources

In order to integrate the proposed system with the current system, a software and hardware interface would need to be first established. A hardware

connection and driver-device is required to support data transfer to the proposed AR application. Additionally, even though there are several displays for viewing a multitude of information, the proposed application can gain its data from a single system. Although, the ship's sonar suite provides the information to the Auxiliary Sonar Visual Display Unit (ASVDU), the same information is also provided to the Combat Control System (CCS). The CCS can provide additional useful information for the new AR application. Therefore, it is desirable to have a single connection from the application to the CCS that feeds sonar data from the sonar suite and fire control solution data from the CCS. The software interface would read data from the hardware device and package it in a format that is readable to the application. Further research on possible hardware and software interfaces should be conducted for the optimal solution.

b. User Interface Design

The information viewed on the AR display should meet the following requirements (established from the previous chapter):

- be a single source for all required information for all users,
- assist the user with creating a mental model,
- be a trustworthy display,
- spatially project the perceived environmental model,
- display classification data for each classified contact,
- and have an adequate size and resolution for precise information gathering.

Organizing the data to meet the requirements above is a significant challenge which is worthy of separate research and will be covered as future work in the next chapter. However, specific user interface (UI) design elements have been extracted from the research and are addressed in this research.

An example of the proposed UI has individual panels that update depending on view or status. Table 15 lists the example panels of the proposed system. A detailed description of these panels follows.

Panel Name	Description
Alert	Provides alerts that require the OOD to direct his attention.
Contact	Displays the focal contact’s spatial representation in the center of the display.
Data	Displays detailed information of the focal contact.
Status	Displays ownship’s parameters, such as course, speed, and depth.
Tactical	Represents the COTD to provide Level 2 SA.

Table 15. The example panels of a proposed AR technology-based solution for the improved submarine control room displays.

Figure 13. An example view of the proposed augmented reality user interface with panels.

The first of the proposed panels, the Tactical Panel, will have a top-down, two-dimensional display with a heading line that is visible at all times. This panel represents the functionality of the currently used COTD. The Alert Panel will list recent status alerts, such as an alert that directs the user to a new contact. The Status Panel will display ownship's parameters such as heading, speed and course. And finally, the Contact Panel will display the information for the contact of focus. In the following discussion, as elements of the proposed applications are addressed, each panel will be identified and will include a detailed description of the information presented for each.

A spatially-projected, environmental model has been determined to be a key element to support improved SA in control. Therefore, each contact that is identified in the CCS is to be displayed at the correct bearing with respect to ownship's control room. As a new contact is identified by sonar and passed to the CCS, an alert will register in center of the screen and then move to the alert panel. Then addressing the alert, and responding to an arrow that directs the shortest path to view the contact, the user turns to the bearing of the new contact. The UI updates the viewable screen to display an icon of the contact. Additionally the following information is presented in the respective panel:

1. Contact number and tracker identifier are updated on the Contact Panel.
2. Actual contact bearing and bearing rate[7] are displayed in the Contact Panel.
3. Solution's generated bearing and bearing rate (if available) is displayed on the Contact Panel.
4. Solution's generated track[8] (if available) is displayed on the Contact Panel.

[7] This is raw information from sonar to permit the verification process of generated solution as discussed in the previous chapter.

5. Classification icon[9] (if available), is updated in the Data Panel.

6. List of elements required to increase the confidence of the contact[10] (if required) is displayed in the Data Panel.

7. The heading display on the Tactical Panel updates to show the user's current field of view.

2. Proposed Display Device

AR technology is presented as a solution because of the many advantages this technology offers. One of these advantages is portability. Researchers are experimenting on solutions to make AR technology even more portable. The display devices have gone through significant development with respect to portability. Screen sizes on portable devices have decreased and resolution on the same devices has increased. A portable device that has the highest percentage of market share in the portable device industry (Becker) is the iPod®. The iPod Touch® has a screen size of 3.5 inches and a resolution of 163 pixels per inch (Apple). Wireless capability is in the third generation (3G) for portable devices such as telephones. Wireless transfer rates are measured in the megabits now. Portable displays are possible to implement in AR technology.

Besides the portable hand-held device as a solution, another option is the head-mounted display (HMD). Using an HMD in the proposed system will provide the most advantages for the solution. An example device used to demonstrate the capabilities and limitations of an HMD in an AR system is Microvision's Nomad™ Personal Display System. This unit has been available

[8] A generated track is a line extending from the front of the contact that suggests direction of motion. This feature provides additional Level 2 SA and contributes to the next level of SA, making contact predictions about contacts.

[9] The icon is modified for the user to understand solution strength and the contact's angle on the bow if known.

[10] Required elements such as number of data legs, time on legs, speed estimates, etc.

since 2002 and has had success in the commercial and defense industries (Business Wire). It is a lightweight (18oz.), video see-through display with a resolution of 800 x 600 pixels. The system can attach to the brim of a ball cap to direct the image to the user's eye. However, the system does have limitations. The display is not in color. It is a monochromic red display with up to 32 shades of grey. It does however, provide an adjustable luminance and can be viewed in varying lighting conditions[11]. The HMD display solution provides the most advantages for the technology presented in this research. The Nomad is only provided as an example display solution. Further research should be conducted to provide the watch team the best solution for the proposed system.

3. Discussion on the Physical Interface Device

An interface is required for the human to interact with the AR system. The proposed system should have settings that are selectable by each user such as display brightness. If the display device selected for the system is a portable hand-held device, such as a PDA, then a built in interface is available. However, if the display device is a HMD, then a portable interface is required. The physical characteristics of the interface are highly dependent on the options available to the user. Therefore, it requires further research to develop the full set of requirements for the system to determine the required interface for the proposed AR solution.

4. The Proposed Registration and Tracking System

The proposed system is required to handle the tracking of each user and registration of the digital information for display. Simply put, this is the process of determining where to put the digital information and maintaining it in the correct position based on the user's location and orientation, regardless of minor head movements. This process is a difficult process that is currently the focus of many

[11] The display is required to be viewed in different lighting conditions because for night operations with the periscope up, the lights in control are off.

researchers. Bimber and Raskar write that “the tracking and registration problem [of AR] is one of the most fundamental challenges” (4).

The first step is to determine the location and orientation of the user in the environment. The proposed system would more than likely use inside-out tracking to accomplish this task since multiple users would need to be tracked. Therefore, each user would have multiple sensors that would determine the location of the user from fixed emitters in the submarine control room. A device that captured the orientation of the user’s head would also be necessary since the information displayed is spatially oriented. This tracking information is captured and transmitted to the application for rendering of the digital information on the display device.

Errors in tracking can result in displaying the wrong information for the location and orientation of the user. Tracking errors exist and require to be compensated for in the design of the system. Further research on the best tracking and error correcting methods for the environment needs to be conducted.

C. ADVANTAGES OF AN AUGMENTED REALITY SYSTEM

The advantages of an AR display system using the features described above over other display technologies is it can meet the solution requirements while delivering a shared, portable, spatially-oriented, heads-up, single display for the control room team member.

1. Spatial Representation of the Contact Environment

The AR system presented in the solution above provides a spatial representation of information based on user position and orientation. Currently, the submarine OOD creates and maintains a spatial representation of the contact environment in his head. The accuracy of this model varies on the experience of the OOD. A more experienced OOD, like a submarine Commanding Officer, maintain this mental model with a high degree of accuracy. Projecting the

contact environment to a spatially visible model supports removing the difficult mental model-making process from the user.

2. A Shared Contact Picture

With a visible model transferred from the key decision maker's mind to a system display, the vision of the user's perceived environment can be shared. A shared picture enables the watch team to provide valuable back up to the OOD. If the watch team knows all the information the OOD is making a decision on, they are able to either support that decision by remaining quiet, or voice their opposition. It also enables the OOD to quickly determine faulty solutions by visually comparing raw data to generated solution data in real time. The resulting advantage from a shared picture is a possible shift of communication from Level 1 SA information to Level 2. Once there is trustworthy information available to all party members, the primary goal of the watch team will shift to determining course of actions based on the available information. This supports Level 2 SA, the SA level addressed as deficient in the previous chapter.

3. A Portable Display System

The AR system proposed in this chapter is portable. Portability provides the user mobility in the control room with access to information where ever the user may stand. The OOD will no longer be restricted to staring at the ASVDU.

4. A Heads-Up, Single Source Display

If the ultimate approved design for the proposed AR system implements an HMD as the display type, then an advantage of the system would be that it offers a single display that provides heads-up features. Therefore, the OOD would be able to have discussions with other team members while both individuals have all the information available for review while talking. This feature can save significant time by allowing the OOD to accomplish multiple tasks with the information available at all times in a display.

D. DISADVANTAGE OF AN AUGMENTED REALITY SYSTEM

There are disadvantages of AR technology as a solution for the control room display system. Problems have been recorded about display devices, and tracking and registration. Most of the disadvantages discussed here would be manifested as annoyances for the user, which may ultimately lead to the user abandoning the AR system for the current display system.

1. AR Display Devices can be Considered Cumbersome

The system display device in an AR system can be cumbersome. If a portable, handheld display was used, the user might become taxed carrying the display in control. It may be dropped and broken. Without a lanyard device, it could be left at a station, making more work for the user to retrieve the display. If a head-mounted display was used, the display could be heavy and cause strain to the neck. In some cases, extended use of an HMD can cause user sickness. Further studies are required to be conducted on the best display device for this proposed system.

2. Tracking and Registration Challenges

There are challenges with tracking and registration in an AR system that present disadvantages. Tracking the user to determine point-of-view, will more than likely be required. However, there are structures in control, such as periscopes and consoles, that may occlude the tracking sensors. Increasing the number of sensors or emitters, increases the load on the tracking system and may lower the display responsiveness. Accuracy is also a noted issue with tracking and registration in AR systems. Some of the common fixes are recalibration of the sensors. This may become an interruption to the decision making process as well. Further research is required to determine the tracking and registration subsystem used for the proposed AR system.

3. Full Use of the Screen Requires Too Much Head Turning

Another disadvantage of the AR system described here is that to view the environmental information, the user is forced to turn his body and head quite frequently to scan the new display. Once again, this could be a source of annoyance for the user, provoking the user to discard the system for the more traditional display system. However, there may be solutions, such as providing a different mode selectable by the physical user interface that allows the user to turn his head slightly in either direction to view the display fully. Obviously further research is required to determine the best design to overcome this technology disadvantage.

E. AN EXAMPLE PD EVOLUTION USING AN AR SOLUTION

This section describes the PD evolution conducted to support the CTA research using the proposed solution system implementing AR technology. Revisiting the evolution in the framework described above can provide valuable insight to the capabilities of the proposed system. This of course is a hypothetical case based on the CTA results, personal experiences, and the proposed display solution using AR technology.

The evolution brief and procedure review is conducted and all personnel in control are on station. The OOD and other key watch standers are wearing an HMD to view the AR display system that presents individual station data in the format necessary to complete their tasks and to view the shared contact picture. The OOD, interested in refreshing his knowledge of the contact picture, scan the virtual display seen through his HMD that spans the upper most portions of control. At each spatially oriented contact, he stops to view the contact’s actual and projected information, the confidence of the solution and the elements that contribute to the confidence level. The OOD notices there are two contacts that are low confidence because they require another data leg to collect information.

Using the current display system to accomplish this task can involve several displays and communication to other watch standers (see Appendix B for options). The OOD scans the ASVDU, searching for data legs on each contact. However, one contact's trace is unreadable due to interference with another contact during the previous leg. The OOD requires the knowledge so request the information from the CEP. The CEP reports that the contact was not tracked at the time requested. The ODD understands now that the contact does not have enough legs of data. However, the OOD does not have a definite understanding of what the FTOW knows, so he requests that the Firecontrol Technician of the Watch (FTOW) report all contacts that require another leg of data. He reports two contacts require further data collection.

Using the proposed system to continue the hypothetical scenario, the OOD looks over his right shoulder and sees a large gap to drive the ship between two contacts that provide the best course to conduct his baffle clear and continue collecting data for these two contacts with a low confidence solution. However, looking down the opposite heading of selected course, the OOD notices that the steer puts another contact in the baffles. Further inspection of the contact status panel shows that the contact has had several legs of data collected, therefore putting the contact in the baffles can be accomplished with no impact to contact management. After the ship steadies on course, sonar reports a new contact. An alert flashes on all the team member's HMD and an arrow directs their attention to the new contact. The OOD sees the new contact information such as bearing and instantaneous bearing rate. The OOD concludes the contact is not a collision threat. The OOD is then alerted that the ship has been on this current leg with sufficient time to collect data for all contact. The OOD knows it's time to conduct another baffle clear.

Again, to accomplish the above tasks using the current display system, a tedious routine has been established. The OOD determines the gap, scans the ASVDU for the contacts that fall within the baffled region (after calculating where that region is located) and then determines if each contact is safe to put in the

baffles by checking the data legs collected on the ASVDU or other displays. When sonar reports a new contact, the OOD moves to the ASVDU to see the contact's bearing and instantaneous bearing rate. Relying on experience, the OOD determines that the bearing rate does not warrant an immediate reaction. The OOD mentally performs some calculations to place the new contact in a spatial model maintained in his head. The OOD looks at his watch and determines that ownship has been on the new course for some time and requests the exact information from the FTOW.

Returning to the proposed AR solution, the OOD directs another course change to clear baffles, and while scanning the tracked contacts, the OOD notices that the two contacts that were previously presented as low confidence are high confidence contacts now with an alert that states two or more legs of data exists. Classification information comes in on the new contact and its icon is automatically updated. The OOD understands that it is a merchant and that the contact will likely stay its course. However, the OOD also notices that another contact's generated track is different than it actual bearing information presented on the display. The display reports that the contact has been tracked for 26 minutes with a high confidence solution. He directs the FTOW to analyze the contact's solution for a possible course or speed change.

The Sonar Supervisor reports that sonar has gained a new contact, and responding to the display alert, the OOD notices that the new contact bearing data, closely matches that of the generated track of the contact lost during the previous baffle clear. The OOD immediately directs the Sonar Supervisor that the contact is a regain and to re-designate the contact as such.

The OOD has met all the requirements and calls the CO to control. After donning the necessary display device, the CO is briefed as usual. The CO wishes to see the raw information and uses the interface to switch modes to "expert." Raw sonar bearing information is displayed with a transparent CCS solution overlay for each contact. The CO is satisfied that all contacts are managed and give the order to the OOD to take the ship to periscope depth.

This hypothetical scenario provides insight to how the proposed system may provide a higher level of SA in the control room, specifically during the contact management phase of a PD evolution. The complexity of the contact management problem was reduced, the accuracy of the Level 2 SA mental model was enhanced therefore permitting the OOD to focus more on predictive SA (Level 3 SA). Providing confidence levels for each solution was able to direct the OOD to the next required task. The OOD owned the contact picture, recognizing a solution difference and was able to quickly determine the next course of action. A single display was used to provide information that would normally take several displays or communications with other watchstanders to determine.

F. SUMMARY

This chapter introduces AR as a potential technology for solving the deficiencies of the current submarine control room display system. It discusses the general requirements for the proposed system. The chapter also covers the advantages of AR as a solution such as providing a shared model of the environment to the watch team. However, there are significant disadvantages that if not addressed in further research could provoke the user to discard the new system entirely.

THIS PAGE INTENTIONALLY LEFT BLANK

VIII. CONCLUSIONS

A. CONCLUSIONS

The cognitive task analysis (CTA) of the periscope evolution (PD) provided insights to the inadequacies of the current displays used in the submarine control room. Individual displays have high impact deficiencies such as the Commanding Officer's Tactical Display (COTD) that is used very seldom due to the lack of trust the Officer of the Deck (OOD) has in individual solutions that the display presents. The CTA presented minor deficiencies as well such as the lack of classification icons on the COTD which limits the OOD's ability to predict future contact activity.

A significant conclusion is that the display system in control does not provide adequate Level 2 situational awareness (SA). Remarkably, this is commonly accepted in the submarine contact management domain. The current solution is to train the OODs to build a mental model of the current contact picture using basic contact information and mathematical formulas. This task is a heavy cognitive task that limits the OODs ability to manage contacts.

A solution to the inadequate displays is achievable. A set of general requirements is presented in the work to address the Level 2 SA deficiencies identified and promote efficiency by decreasing communication to support Level 1 SA and decrease the need to move to other displays for more information. The result would increase watch team efficiency at managing contacts and safe navigation of the ship.

An Augmented Reality (AR) system is a candidate solution that provides all the necessary requirements identified in the detailed solution to the current inadequate display system. The AR system detailed in Chapter VII provides a solution that is a shared, portable, spatially-oriented, heads-up, single display for the control room team member.

B. FUTURE WORKS

1. Identify the Specification for the New Display System

The conducted in this thesis identifies the general requirements for an improved display system in control. More work needs to be done to provide an exact specification of the newly proposed control room displays. Using a systems development approach such as Systems Engineering can provide the specifications required to create a useful design.

2. A Human Systems Integration Study

Although this work presents a solution technology with AR, it is important to note that a Human Systems Integration (HSI) study has not been conducted to support this technology for this domain. Further research needs to be conducted to determine if the user will find AR as a comfortable, usable solution. Items that need to be addressed in the study are the identification of the best display type, a required interface solution as well as the proper registration and tracking techniques for the submarine control room environment. However, the most vital research may be to determine an optimal User Interface development to support continued use and support for the new display system.

3. Measuring the Offered Solution's Situational Awareness Improvement

This research asserts that the current submarine control room displays provides insufficient Level 2 SA. This assertion is a product of studying the results of the CTA. However, for a more conclusive result the assertion requires to be tested and measured. Therefore, it is recommended that future work would test the Level of SA achieved by the current system. Then after the prototype of the AR solution is complete, test it to record the Level of SA achieved. A comparison of the results could provide a validation of this works assertion that the current displays provide insufficient SA for the watch team.

LIST OF REFERENCES

Adam, Eugene, C. “Fighter Cockpits of the Future.” *Digital Avionics Systems Conference, 1993. 12th DASC., AIAA/IEEE*, 318-323.

Becker, David. “Its all about the iPod.” CNet News. Oct. 12, 2004. Last accessed Sep. 22, 2008. <http://news.cnet.com/Its-all-about-the-iPod/2100-1041_3-5406519.html>

Bimber, Oliver and Ramesh Raskar. *Spatial Augmented Reality: Merging Real and Virtual Worlds.* Wellesley, MA: A K Peters, 2005. 1-8.

Boyd, John. “Patterns of Conflict.” *Defense and the National Interest.* Dec. 1986. Last accessed Aug. 27, 2008. < http://www.d-n-i.net/boyd/pdf/poc.pdf>

Boyd, John. “The Essence of Winning and Losing.” *War, Chaos and Business.* Jun. 28, 1995. Last accessed Aug. 27, 2008. <http://www.chetrichards.com/modern_business_strategy/boyd/essence/eowl_frameset.htm>

Business Wire. "Microvision's Nomad Personal Display System Increases Precision Measurement Efficiency by more than 50% in Boeing Field Trial." FindArticles.com. Jul. 16, 2002. Last accessed Sep. 23, 2008.<http://findarticles.com/p/articles/mi_m0EIN/is_2002_July_16/ai_89067735>

Capps, Micheal. Naval Postgraduate School. “Virtual Retinal Display Technology.” 1999. Last accessed Aug. 28, 2008. <http://www.cs.nps.navy.mil/people/faculty/capps/4473/projects/fiambolis/vrd/vrd_full.html>

Chipman, Susan F., Jan Maarten Schraagen, and Valerie L. Shalin. “Introduction to Cognitive Task Analysis.” Cognitive Task Analysis. Ed. Jan Maarten Schraagen, et al. New Jersey: Lawrence Erlbaum. 2000. 3-23.

Endsley, Mica, R. “Toward a Theory of Situation Awareness in Dynamic Systems.” *Human Factors: The Journal of Human Factors and Ergonomics*. 37.1 (March 1995): 32-64.

———. “Measurement of Situation Awareness in Dynamic Systems.” *Human Factors: The Journal of Human Factors and Ergonomics*. 37.1 (March 1995): 65-84.

Endsley, Mica, R. and William M. Jones, “Situation Awareness Information Dominance & Information Warfare.” (No. AL/CF-TR-1997-0156). Wright-Patterson AFB, OH: United States Air Force Armstrong Laboratory.

McClernon, Christopher K. “Human Performance Effects of Adaptive Automation of Various Air Traffic Control Information Processing Functions.” North Carolina State. Raleigh, NC: 2003.

Milgram, Paul and Fumio Kishino. “A Taxonomy of Mixed Reality Visual Displays.” Mechanical & Industrial Engineering University of Toronto. Ergonomics in TeleOperation and Control Laboratory. Last accessed Aug. 28, 2008. <http://vered.rose.utoronto.ca/people/paul_dir/IEICE94/ieice.html>

Saunders, Stephen, ed. *Jane’s Fighting Ships.* Alexandria, Va.: Jane's Information Group Inc., 2007.

United States. Department of the Navy. Commander In Chief, U.S. Pacific Fleet. “Court of Inquiry into the Circumstances Surrounding the Collision Between USS Greenville (SSN 772) and Japanese M/V Ehime Maru That Occurred Off the Coast of Oahu, Hawaii on 9 February 2001.” Apr. 23, 2001.

United States. Department of the Navy. Commander 7th Fleet. “Command Investigation of the Submerged Grounding of USS San Francisco (SSN 711) Approximately 360 nm Southeast of Guam That Occured on 8 January 2005.” Feb. 27, 2005.

United States. Department of the Navy. NewsStand. Photo ID 050127-N-4658L-030. Jan. 27, 2005. Last accessed Aug. 29, 2008. <http://www.news.navy.mil/view_single.asp?id=21183>

Zachary, Wayne W., Joan M. Ryder, and James H. Hicinbothom. “Building Cognitive Task Analyses and Models of a Decision-making Team in a Complex Real-time Environment.” Cognitive Task Analysis. Ed. Jan Maarten Schraagen, et al. New Jersey: Lawrence Erlbaum. 2000. 365-383.

Zachary, Wayne W., Joan M. Ryder, and James H. Hicinbothom. “Cognitive Task Analysis and Modeling of Decision Making in Complex Environments.” *Decision Making Under Stress: Implications for Individual and Team Training.* Ed. Janis A. Cannon-Bowers, et al. Washington, DC: American Psychological Association, 2000. 315-344.

APPENDIX A: COGNITIVE TASK ANALYSIS (PREPARATION SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reason & Notes***
Review procedures: Review COSO on PD evolution Review OP on PD evolution	 OOD OOD		 Info Info	 Visual Visual	Stored cognitive knowledge	The evolution advances rapidly. There is little time to receive direction from procedures during the evolution.
Review *Emergency Deep* procedure with the Ships Handling team: "Review the *Emergency Deep* procedure for the ship handling team." Diving Officer reads procedure and asks questions	 OOD Dive	 Dive Party	 Directive Info	 Auditory Auditory	Stored cognitive knowledge Stored cognitive knowledge	If and when the procedure is used it must be from memory. All emergency procedures are conducted from memory. OOD is supervising.
Call all supervisors to control for PD evolution brief "Supervisors to control for PD evolution brief."	 OOD	 All Sups	 Directive	 Auditory	Following supervisors to control: Sonar, Radio and Navigation	
Conduct evolution brief: "Attention in control for brief" Supervisors brief	 OOD Supervisor	 All All	 Directive Status	 Auditory Auditory	 Stored cognitive knowledge	OOD directs brief. Supervisors are briefing party of ship/ environmental status. Information addressed: 1. weather 2. acoustical noise level 3. time of day 4. expected visibility 5. current contacts, etc
Personnel return to their stations: "Take station for PD evolution"	 OOD	 All	 Directive	 Auditory	All supervisors and operators take station to conduct PD evolution	

APPENDIX A: COGNITIVE TASK ANALYSIS (PREPARATION SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reason & Notes***
Line up the periscopes:					Switches and periscope settings are manipulated to match the environmental conditions.	
“Line up the periscopes for PD operations.”	OOD	JOOD	Directive	Auditory		
Change ships depth consistent with sonar search depth:					Ship’s state changed.	*Surface layer data may be requested/briefed at evolution brief depending on experience of team*
Determine required search depth [SELECT]:					Stored cognitive knowledge.	
View SVP	OOD	SVP[1]	Query	Visual		Sonar accomplishes same task of reviewing SVP. May possess more experience with analyzing SVP.
“Report surface layer depth”	OOD	Sonar	Directive	Auditory		
Report	Sonar	OOD	Status	Auditory		
View ships depth	OOD	SSP	Query	Visual	Stored cognitive knowledge.	
“Change depth”	OOD	Dive	Directive	Auditory		
Change ships speed consistent with sonar search speed:					Ship’s state changed.	
View ships speed	OOD	SSP	Query	Visual		
Determine ordered bell	OOD		Query	Cognitive		
“Change speed”	OOD	Helm	Directive	Auditory		

[1] SVP is the Sound Velocity Profile. A document that plots the sound velocity versus depth.

APPENDIX B: COGNITIVE TASK ANALYSIS (CONTACT MANAGEMENT SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Determine current contact situation [SELECT]:					Stored cognitive knowledge	To build and maintain mental model.
Build mental model of contact [FOR EACH]:					Stored cognitive knowledge	
Check contact bearing	OOD	*ASVDU*	Query	Visual	Stored cognitive knowledge	
Determine contact bearing rate [SELECT]:					Stored cognitive knowledge	
User experience	OOD	*ASVDU*	Query	Cognitive	Recall bearing rate patterns	
Short duration calculation	OOD	*ASVDU*	Calculation	Cognitive	Calculate bearing rate	
“Report bearing rate”:	OOD	FTOW	Query	Auditory	FTOW performs action	
Retrieval	FTOW	*CCS*	Query	Visual		
Report	FTOW	OOD	Status	Auditory	Stored cognitive knowledge	
Apply best speed	OOD		Calculation	Cognitive		
Check top-down display [SELECT]:[1]					Stored cognitive knowledge	
Geographic Plot	OOD	*Geo*	Query	Visual		Processed data (may not be up-to-date)
COTD	OOD	*COTD*	Query	Visual		
NAV Plot	OOD	*Nav*	Query	Visual		
“Report all contacts”	OOD	Sonar	Directive	Auditory	Sonar performs action	
Report	Sonar	OOD[2]	Status	Auditory		By procedure, report is conducted on each leg[3]

[1] OOD may elect to view one or more top-down displays

[2] Although Sonar Supervisor is reporting to the OOD, his communication is over the Open Microphone. Therefore, all personnel in control can hear his reports. This is important because all evaluating stations use Sonar information to (at least) initiate a problem-solving process.

[3] A *leg* is a common submarine term used to identify a period of time the ship spends on a constant course collecting data on all contacts

APPENDIX B: COGNITIVE TASK ANALYSIS (CONTACT MANAGEMENT SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Verify all contacts are up-to-date in CCS system [SELECT]:[4]					All solutions updated	Ensures that the current 2D display is up-to-date since CO will use to compare his analysis of ASVDU to verify system solutions are close.
Contact estimated range and course brackets [FOR EACH]:					Stored cognitive knowledge	
View contact bearing	OOD	*ASVDU*	Query	Visual	Stored cognitive knowledge	ASVDU is real-time data
Determine bearing rate [SELECT]:					Stored cognitive knowledge	
Recall	OOD	*ASVDU*	Query	Cognitive	Recall bearing rate patterns	Trained to recognize bearing rates.
Short duration calculation	OOD	*ASVDU*	Calculation	Cognitive		Math based on slope calculation.
"Report bearing rate":	OOD	FTOW	Query	Auditory	FTOW performs action	Communication chain resulting in information passed from display to OOD for decision-making.
Retrieval	FTOW	*CCS*	Query	Visual		
Report	FTOW	OOD	Status	Auditory		
Ownship's[5] speed [SELECT]:					Stored cognitive knowledge	
Recall	OOD		Query	Cognitive	Recall ownship's speed	
Check	OOD	*SSP*	Query	Visual		
Contact estimate of speed [SELECT]:					Stored cognitive knowledge	
Recall	OOD		Query	Cognitive	Recall contact's estimated speed	May have been announced by Sonar previous to this step
Request:						Sonar uses sources to determine best estimate of contact speed.
"Report estimated speed"	OOD	Sonar	Query	Auditory	Sonar performs action	
Report	Sonar	OOD	Status	Auditory		

[4] This step will be conducted normally in conjunction with the previous step of determining the current contact situation.
[5] *Ownship* is a common submarine term used for clarification, so as to differentiate the originator's ship from other ships.

APPENDIX B: COGNITIVE TASK ANALYSIS (CONTACT MANAGEMENT SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Verify all contacts are up-to-date in CCS system [SELECT]: (*cont.*)						
Compare estimated range and course brackets to contact solution:	OOD	*COTD*	Query	Visual	Stored cognitive knowledge of solution status	
[IF] contact requires update:						
"Update contact"	OOD	FTOW	Directive	Auditory	FTOW updates solution	
Report	FTOW	OOD	Status	Auditory	Updated cognitive knowledge of solution status	
"Verify all solutions are up-to-date"	OOD	FTOW	Directive	Auditory	FTOW performs action	
Update contact [FOR EACH]	FTOW	*CCS*	Operation	Manual		
Report	FTOW	OOD	Status	Auditory	Stored cognitive knowledge of all solutions status	
Verify all contacts have at minimum two legs of sonar data collected [SELECT]:					Stored cognitive knowledge	For the visual queries, the OOD is looking to ensure that there are sonar traces for each contact on at least two legs. Fusion plot was used to easily distinguish traces in high-contact density legs.
View sonar bearing history [SELECT]:					Stored cognitive knowledge	
ASVDU [FOR EACH]	OOD	*ASVDU*	Query	Visual		
Fusion[6] [FOR EACH]	OOD	*Fusion*	Query	Visual		Important step that ensures baffle clear direction will not obscure contact that requires data collection.
"Report all contacts that require another leg of data"	OOD	FTOW	Directive	Auditory	FTOW performs action	
Retrieval	FTOW	*CCS*	Operation	Manual		
Report	FTOW	OOD	Status	Auditory	Stored cognitive knowledge	

[6] In application, not all submarine CCS systems are equipped with the digital Fusion plot and therefore require a CEP (paper and marker version).

APPENDIX B: COGNITIVE TASK ANALYSIS (CONTACT MANAGEMENT SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Conduct a baffle clear:					Ownship's state changed	
Ownship's heading [SELECT]:					Stored cognitive knowledge	
Recall	OOD		Query	Cognitive	Recall ownship's heading	
Check [SELECT]:					Stored cognitive knowledge	
ASVDU	OOD	*ASVDU*	Query	Visual		
SSP	OOD	*SSP*	Query	Visual		
Select course based on following:						
Required course change to clear baffles	OOD		Query	Cognitive	Recall required course change	By procedure, must change course to clear baffles to ensure knowledge of all contacts
Contacts requiring further data collection	OOD		Query	Cognitive	Recall contacts requiring data	
Available courses [SELECT]:					Stored cognitive knowledge	Available courses based on headings that would not drive straight at a contact
ASVDU	OOD	*ASVDU*	Query	Visual		
COTD	OOD	*COTD*	Query	Visual		
"Change course"	OOD	Helm	Directive	Auditory	Helm performs action	
Report	Helm	OOD	Status	Auditory	Stored cognitive knowledge	
New sonar contact:						
Discovery [SELECT]:					Stored cognitive knowledge	
"Gain new sonar contact"	Sonar	OOD	Status	Auditory		

APPENDIX B: COGNITIVE TASK ANALYSIS (CONTACT MANAGEMENT SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
New sonar contact: (*cont.*)						
Discovery [SELECT]: (*cont.*)					Stored cognitive knowledge	
Observe unknown trace:	OOD	*ASVDU*	Query	Visual		
"Report new trace"	OOD	Sonar	Directive	Auditory	Sonar performs action	
Report	Sonar	OOD	Status	Auditory	Stored cognitive knowledge	
Analyze contact data[7]	OOD	*ASVDU*	Query	Visual	*Not discussed*	Verify no immediate action required to avoid collision.
Verify not regain of previous contact [SELECT]:					Stored cognitive knowledge	
View contact solution [FOR EACH]:						
Compare new contact bearing to solution bearing	OOD	*COTD*	Query	Visual		
View previously held contact trace [FOR EACH]:						
Compare new contact bearing to generated[8] trace	OOD	*Fusion*	Query	Visual		Fusion plot used when previous contacts solutions are underdeveloped due to insufficient data.
[IF] Contact is regain of old contact:						
"Reassign new contact"	OOD	Sonar	Directive	Auditory	Sonar performs action	Reassigned to maintain data collection on previous contact.
Report	Sonar	OOD	Status	Auditory	Stored cognitive knowledge	
"Report classification and best speed"	OOD	Sonar	Directive	Auditory	Sonar performs action	Classification and speed data used to determine range and course brackets
Report	Sonar	OOD	Status	Auditory	Stored cognitive knowledge	

[7] This step is purposely vague for classification reasons. However, it is important to note that the OOD does have to analyze each new contact to ensure collision does not occur. The process to determine if action is required and which action to take is classified.

[8] *Generated* refers to the process of extending the trace by analyzing the previous data and making a predictive estimate of the extended trace's current location.

APPENDIX B: COGNITIVE TASK ANALYSIS (CONTACT MANAGEMENT SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Ensure minimum time to gather information on all contacts has elapsed on current course:						
“Report when there is sufficient sonar data for all contacts”	OOD	FTOW	Directive	Auditory	FTOW performs action	FTOW will monitor time and inform OOD when required time has elapsed.
Report	FTOW	OOD	Status	Auditory	Stored cognitive knowledge	
Select a safe course for PD:					Stored cognitive knowledge	
Verify all contacts are up-to-date in CCS system *(see previous step)*					Contacts are up-to-date	
Select a sufficiently large bearing gap between contacts [SELECT]:					Stored cognitive knowledge	
ASVDU	OOD	*ASVDU*	Query	Visual		
COTD	OOD	*COTD*	Query	Visual		COTD selected at times because ease of viewing contact picture.
Verify the following at the gap [FOR EACH]:						
Verify the following for a contact [FOR EACH]:						
Determine contact position and drift at gap	OOD	*ASVDU*	Query	Cognitive	Stored cognitive knowledge	When ownship’s heading changes, contact bearing rates change (ownship’s heading is a component in calculating relative bearing rate with contact). ASVDU does not display system solution. Thus, cognitive process.
[IF] contact on left and drift is right or on right and drift is left	OOD		Query	Cognitive		
Select new gap						
Determine if closest contact and in baffles	OOD	*ASVDU*	Query	Cognitive	Stored cognitive knowledge	
[IF] closest and in baffles	OOD		Query	Cognitive		
Select new gap						
Verify course selection on COTD	OOD	*COTD*	Query	Visual		

APPENDIX B: COGNITIVE TASK ANALYSIS (CONTACT MANAGEMENT SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Obtain concurrence form watch team on course selected for PD:					Stored cognitive knowledge	Important to obtain concurrence from watch team to allow watch team to backup OOD decision.
“Intensions for PD course”	OOD	All	Status	Auditory	All team members analyze course to ensure safe course for PD	
Report	JOOD	OOD	Status	Auditory		
Report	Sonar	OOD	Status	Auditory		
Report	FTOW	OOD	Status	Auditory		
[IF] one report does not provide concurrence [SELECT]:						
Explain in detail to source						
Select new course						
Change course to PD course:					Ownship’s state changed	
“Change course”	OOD	Helm	Directive	Auditory		
Report	Helm	OOD	Status	Auditory		
Change speed to speed required for PD:					Ownship’s state changed	
Ownship’s speed [SELECT]:						
Recall	OOD		Query	Cognitive	Recall ownship’s speed	
Check	OOD	*SSP*	Query	Visual	Stored cognitive knowledge	
“Change speed”	OOD	Helm	Directive	Auditory		
Report	Helm	OOD	Status	Auditory		

APPENDIX B: COGNITIVE TASK ANALYSIS (CONTACT MANAGEMENT SEGMENT)

Step / Actions	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Brief and obtain permission from CO:					Permission from CO	
Spatially describe contact [FOR EACH]:						CO analyzes ASVDU to determine his contact picture (domain expert) then compares OOD mental model to ensure accuracy.
Point to location	OOD	CO	Status	Auditory		
Report range	OOD	CO	Status	Auditory		
Signal drift	OOD	CO	Status	Auditory		
[IF] CO does not concur						
Select new course						
Raise the periscope and test the early warning device:					Ownship’s state changed	
Check ownship’s speed	OOD	*SSP*	Query	Visual	Stored cognitive knowledge	
Verify speed is less than required to raise periscope	OOD		Query	Cognitive	Recall speed limitations	Provides safety to scope
“Raise the scope and test the early warning device”	OOD	JOOD	Directive	Auditory	JOOD performs action	
Report	JOOD	OOD	Status	Auditory	Stored cognitive knowledge	

APPENDIX C: COGNITIVE TASK ANALYSIS (ASCENT SEGMENT)

Step / Action	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Raise the scope and test the early warning device:						
Verify ship speed is safe to raise scope	OOD	*SSP*	Query	Visual	Stored cognitive knowledge	
"Raise scope and test the early warning receiver"	OOD	JOOD	Directive	Auditory	Scope raised EW device tested	EW device detects radar emissions
Report	JOOD	OOD	Status	Auditory	Stored cognitive knowledge	
Take the scope	OOD	*Scope*	Query	Visual	Environment visible	Limited field of view through scope
Proceed to PD:						
"All stations, Conn, proceeding to PD"	OOD	All	Status	Auditory	No noise in control	Noise in control is limited to that which controls ship and emergency alerts
"Proceed to PD"	OOD	Dive	Directive	Auditory	Ownship's state changed	
Scan for contacts:						
Conduct quick search routine	OOD	*Scope*	Status	Manual	Stored cognitive knowledge	Required to determine if any contact is close enough to cause emergency action.
ESM detection report	ESM	All	Status	Auditory	Stored cognitive knowledge	In conditions where visibility is limited then radar emissions can be only source of eminent danger.
"No close contacts"	OOD	All	Status	Auditory	Noise resumes in control	All personnel understand that ship is out of danger.

APPENDIX C: COGNITIVE TASK ANALYSIS (ASCENT SEGMENT)

Step / Action	***Originator***	***Receiver***	***Type***	***Mode***	***Result***	***Reasons & Notes***
Correlate sonar contacts with visible contacts:					All sonar contacts correlated to visual contacts	
"Direct me to next sonar contact"	OOD	JOOD	Directive	Auditory	JOOD performs actions	JOOD views contact to see current bearing vs. periscope heading
Determine difference in scope view from contact bearing:						
View scope heading	JOOD	SSP	Query	Visual	Stored cognitive knowledge	
View contact bearing	JOOD	SSP	Query	Visual	Stored cognitive knowledge	
Direct scope operator	OOD	All	Status	Auditory	OOD moves scope to align it by direction of JOOD	Directions like "come left 20 degrees"
Search	OOD	All	Status	Auditory	Trains scope	**Cognitive task** OOD does not have degrees indicator viewable to him (guess)
[IF] contact exists:						
Classify contact	OOD	All	Status	Auditory	Stored cognitive information.	Personnel whiteboards are updated to reflect changes (not all displays can be identified by contact ID no.)
Re-designate contact number	OOD	All	Directive	Auditory	Personnel update displays and stored cognitive knowledge	
Conduct observation:						
Bearing	OOD	All	Status	Auditory	Digitally passed to CCS Spoken for all personnel to record information on their cognizant plot	**Cognitive task** Visual detection and collection is truth. Calculations are used to determine range based on divisions and FOV. Experience is used to determine AOB
Range	OOD	All	Status	Auditory		
Angle on the bow (AOB)	OOD	All	Status	Auditory		
Update displays:						
CCS	FTOW	CCS	Operation	Manual		
Geographic Plot	Geo	Plot	Operation	Manual		

APPENDIX D: LEVEL OF SA FOR TASKS IN THE CONTACT MANAGEMENT SEGMENT OF THE CTA

Step / Actions	***Level of SA***
Determine current contact situation [SELECT]:	Level 2 SA
Build mental model of contact [FOR EACH]:	Level 2 SA
Check contact bearing	Level 1 SA
Determine contact bearing rate [SELECT]:	Level 1 SA
User experience	
Short duration calculation	
“Report bearing rate”:	
Retrieval	
Report	
Apply best speed	Level 1 SA
Check top-down display [SELECT]:	Level 2 SA
Geographic Plot	
COTD	
NAV Plot	
“Report all contacts”	Level 2 SA
Report	
Verify all contacts are up-to-date in CCS system [SELECT]:	Level 2 SA
Contact estimated range and course brackets [FOR EACH]:	Level 2 SA
View contact bearing	Level 1 SA
Determine bearing rate [SELECT]:	Level 1 SA
Recall	
Short duration calculation	
“Report bearing rate”:	
Retrieval	
Report	
Ownship’s speed [SELECT]:	Level 1 SA
Recall	
Check	
Contact estimate of speed [SELECT]:	Level 1 SA
Recall	
Request:	
“Report estimated speed”	
Report	
Compare estimated range and course brackets to contact solution:	Level 2 SA
[IF] contact requires update:	
“Update contact”	
Report	
“Verify all solutions are up-to-date”	Level 2 SA
Update contact [FOR EACH]	
Report	

APPENDIX D: LEVEL OF SA FOR TASKS IN THE CONTACT MANAGEMENT SEGMENT OF THE CTA

Step / Actions	***Level of SA***
Verify all contacts have at minimum two legs of sonar data collected [SELECT]:	Level 1 SA
View sonar bearing history [SELECT]:	Level 1 SA
ASVDU [FOR EACH]	
Fusion [FOR EACH]	
"Report all contacts that require another leg of data"	Level 1 SA
Retrieval	
Report	
Conduct a baffle clear:	
Ownship's heading [SELECT]:	Level 1 SA
Recall	
Check [SELECT]:	
ASVDU	
SSP	
Select course based on following:	
Required course change to clear baffles	
Contacts requiring further data collection	Level 1 SA
Available courses [SELECT]:	Level 1 SA
ASVDU	
COTD	
"Change course"	
Report	
New sonar contact:	Level 2 SA
Discovery [SELECT]:	
"Gain new sonar contact"	Level 1 SA
Observe unknown trace:	
"Report new trace"	Level 1 SA
Report	
Analyze contact data	
	Level 1 SA
Verify not regain of previous contact [SELECT]:	
View contact solution [FOR EACH]:	Level 2 SA
Compare new contact bearing to solution bearing	
	Level 1 SA
View previously held contact trace [FOR EACH]:	
Compare new contact bearing to generated trace	
	Level 1 SA
[IF] Contact is regain of old contact:	
"Reassign new contact"	
Report	
"Report classification and best speed"	
	Level 2 SA
Report	

APPENDIX D: LEVEL OF SA FOR TASKS IN THE CONTACT MANAGEMENT SEGMENT OF THE CTA

Step / Actions	***Level of SA***

Ensure minimum time to gather information on all contacts has elapsed on current course:
 	
    "Report when there is sufficient sonar data for all contacts"
    Report
	Level 1 SA

Select a safe course for PD:
    Verify all contacts are up-to-date in CCS system
    (see previous step)
 	
    Select a sufficiently large bearing gap between contacts [SELECT]:
        ASVDU
        COTD
 	
    Verify the following at the gap [FOR EACH]:
        Verify the following for a contact [FOR EACH]:
            Determine contact position and drift at gap
            [IF] contact on left and drift is right or on right and drift is left
                Select new gap
 	
            Determine if closest contact and in baffles
            [IF] closest and in baffles
                Select new gap
 	
    Verify course selection on COTD
	Level 3 SA
	Level 2 SA
	
	Level 1 SA
	
	Level 3 SA
	
	Level 3 SA
	
	Level 3 SA

Obtain concurrence form watch team on course selected for PD:
    "Intensions for PD course"
 	
    Report
 	
    Report
 	
    Report
 	
    [IF] one report does not provide concurrence [SELECT]:
        Explain in detail to source
        Select new course
	Level 3 SA

Change course to PD course:
    "Change course"
    Report
	Level 1 SA

Change speed to speed required for PD:
    Ownship's speed [SELECT]:
        Recall
        Check
 	
    "Change speed"
 	
    Report
	
	Level 1 SA

APPENDIX D: LEVEL OF SA FOR TASKS IN THE CONTACT MANAGEMENT SEGMENT OF THE CTA

Step / Actions	***Level of SA***
Brief and obtain permission from CO:	Level 3 SA
Spatially describe contact [FOR EACH]:	
Point to location	Level 2 SA
Report range	Level 2 SA
Signal drift	Level 3 SA
[IF] CO does not concur	
Select new course	
Raise the periscope and test the early warning device:	
Check ownship's speed	Level 1 SA
Verify speed is less than required to raise periscope	Level 1 SA
"Raise the scope and test the early warning device"	
Report	

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California